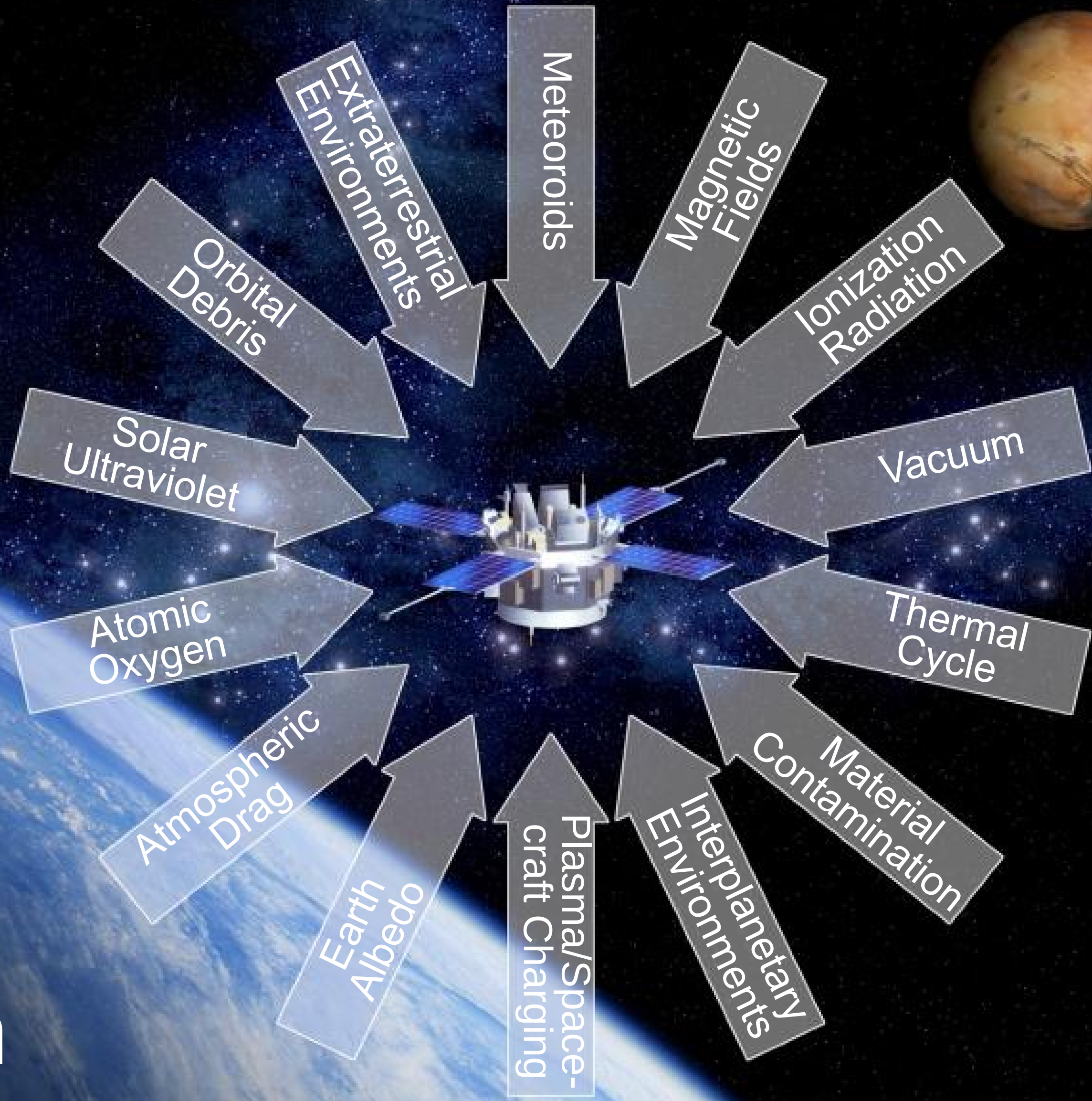
Influence of Natural Environments in Spacecraft Design, Development, and Operation



Dr. Dave Edwards
Flight Mechanics and Analysis Division


THE KIND OF ATTITUDE THAT COULD REALLY TAKE THE WIND OUT OF THE SAILS OF THE SPACE PROGRAM
MOON, MARS, JUPITER, I GOTTA TELL YOU... I'M NOT SEEING A WHOLE LOT OF DIFFERENCE
Comic videos www.mrboffo.com

Outline

- Background
- Impact
- Guideline Process
- Environments
- Interactions
    - o Contamination
    - o Spacecraft Charging
    - o Atomic Oxygen
    - o Thermal Vacuum
    - o Electromagnetic Radiation
    - o Micrometeoroids / Orbital Debris
    - o Ionizing Radiation
- Space System Anomaly
- Summary

Background

- Spacecraft are growing in complexity and sensitivity to environmental effects.
- The spacecraft engineer must understand and take these effects into account in building reliable, survivable, and affordable spacecraft.
- Too much protections, however, means unnecessary expense while too little will potentially lead to early mission loss.
- The ability to balance cost and risk necessitates an understanding of how the environment impacts the spacecraft and is a critical factor in its design.
- This presentation is intended to address both the space environment and its effects with the intent of introducing the influence of the environment on spacecraft performance.

THE IMPACT OF THE SPACE ENVIRONMENT ON SPACE SYSTEMS†

Distribution by Anomaly Diagnosis

Diagnosis	Number of Forms
ESD - Internal Charging	74
ESD - Surface Charging	59
ESD - Uncategorized	28
Surface Charging	1
Total ESD & Charging	**162**
SEU - Cosmic Ray	15
SEU - Solar Particle Event	9
SEU - South Atlantic Anomaly	20
SEU - Uncategorized	41
Total SEU	**85**
Solar Array - Solar Proton Event	9
Total Radiation Dose	3
Materials Damage	3
South Atlantic Anomaly	1
Total Radiation Damage	**16**
Micrometeorid/Debris Impact	10
Solar Proton Event - Uncategorized	9
Magnetic Field Variability	5
Plasma Effects	4
Atomic Oxygen Erosion	1
Atmospheric Drag	1
Sunlight	1
IR background	1
Ionospheric Scintillation	1
Energetic Electrons	1
Other	2
Total Miscellaneous	**36**

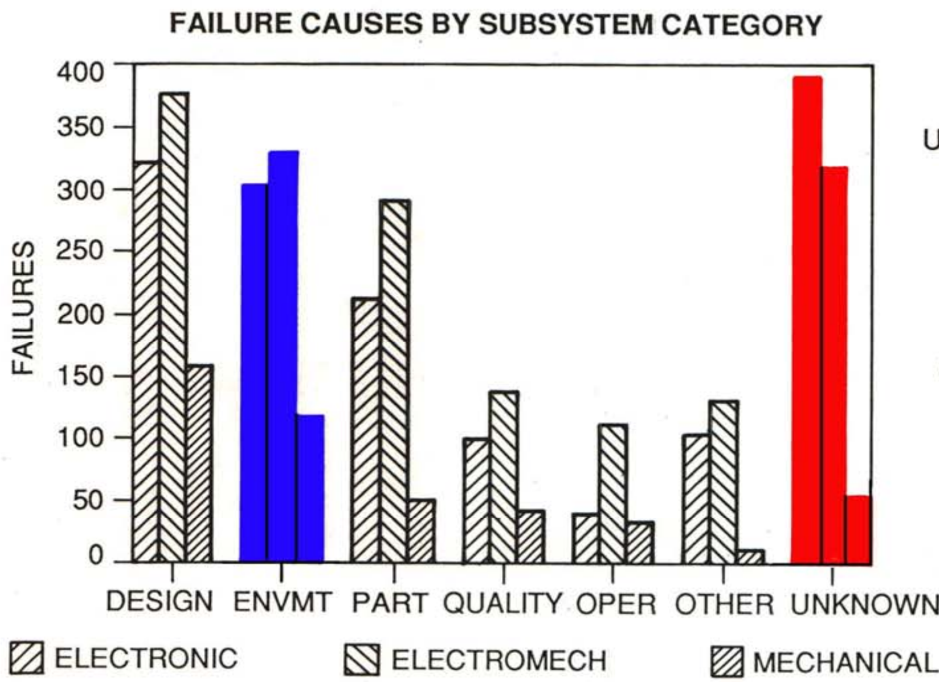
†Koons, H.C., J. E. Mazur, R. S. Selesnick, J. B. Blake, J. F. Fennell, J. L. Roeder, and P. C. Anderson, "The Impact of the Space Environment on Space Systems", presented at Charging Conference, Nov 1998.

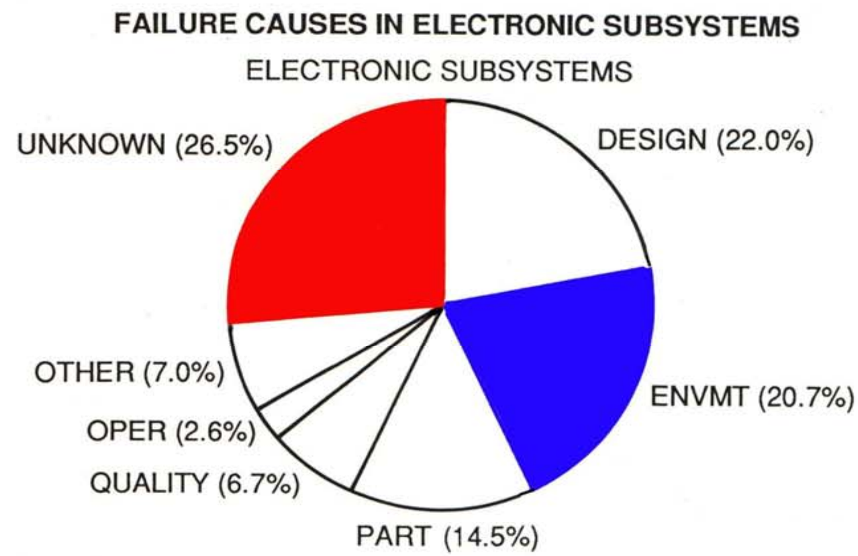
Missions Lost/Terminated Due to Space Environment

Vehicle	Date	Diagnosis
DSCS II (9431)	Feb 73	Surface ESD
GOES 4	Nov 82	Surface ESD
DSP Flight 7	Jan 85	Surface ESD
Feng Yun 1	Jun 88	ESD
MARECS A	Mar 91	Surface ESD
MSTI	Jan 93	Single Event Effect
Hipparcos*	Aug 93	Total Radiation Dose
Olympus	Aug 93	Micrometeoroid Impact
SEDS 2*	Mar 94	Micrometeoroid Impact
MSTI 2	Mar 94	Micrometeoroid Impact
IRON 9906	1997	Single Event Effect
INSAT 2D	Oct 97	Surface ESD

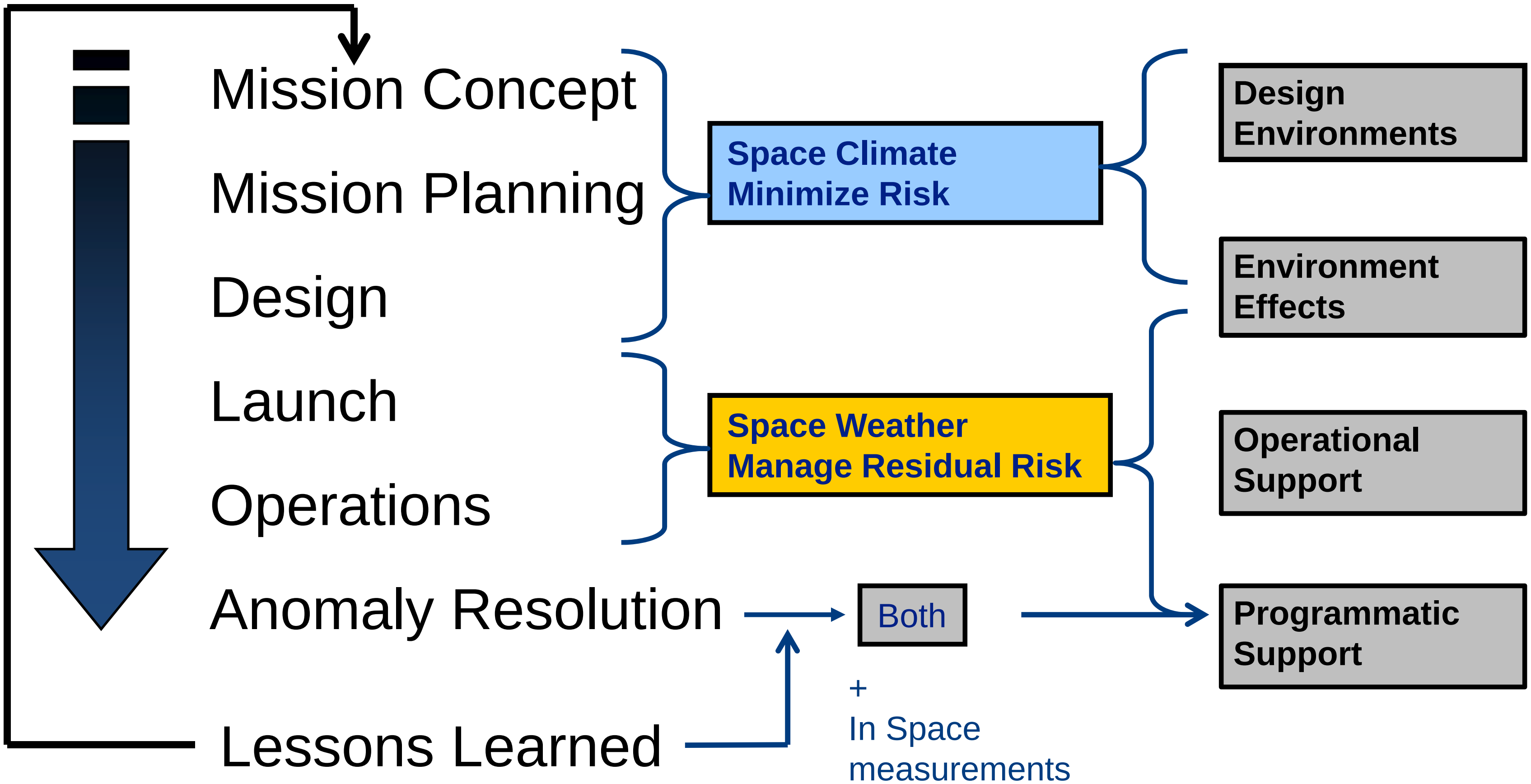
*Mission had been completed prior to termination

Subsystem In-flight Failure Causes (Hecht, 1985)





- 600 satellites currently in orbit (1999) are worth $50-$100B with 235 insured for $20B
- 1500 space payloads are expected to be launched 2000 – 2010 with a potential insured value of $80 billion!
- 481 US satellites currently manifested from 2011 - 2020 at a total cost of $150B



Space Environments information is critical during all phases of spacecraft life cycle

Guideline Process

1. Define the environments

2. Analyze potential environmental interactions that could occur

3. Implement mitigation strategies to minimize/eliminate adverse interactions

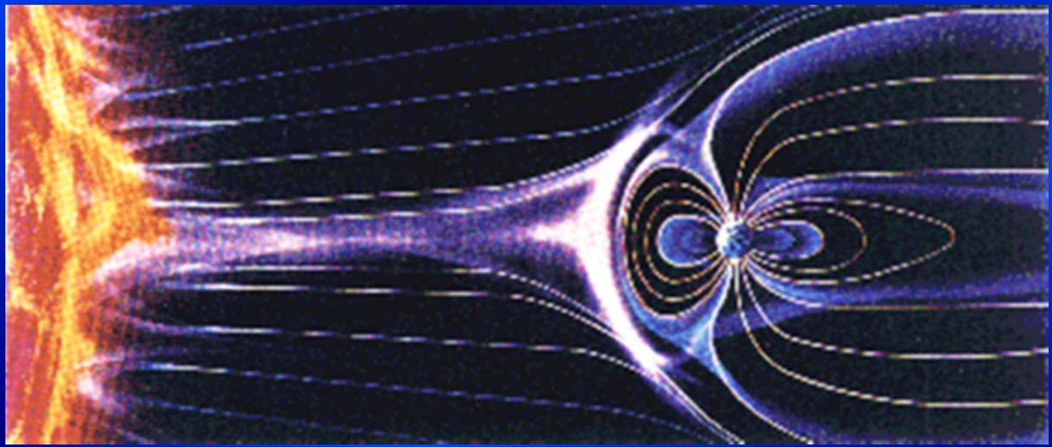
4. Ground test to evaluate engineering performance in relevant environment

5. Analyze the data from the spacecraft to determine effectiveness of the process

6. Integrate information learned into process improvement

Environments

- Atmospheres
- Solar UV Flux
- Atomic Oxygen
- Space Vacuum
- Thermal Cycling
- Plasma / Charging Environments
- Micro-Meteoroid/Space Debris
- Spacecraft Induced Environment

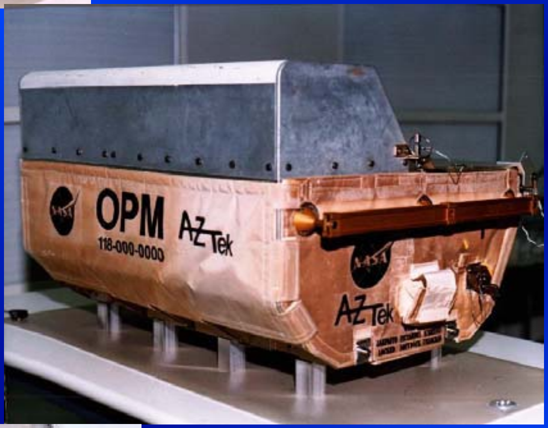


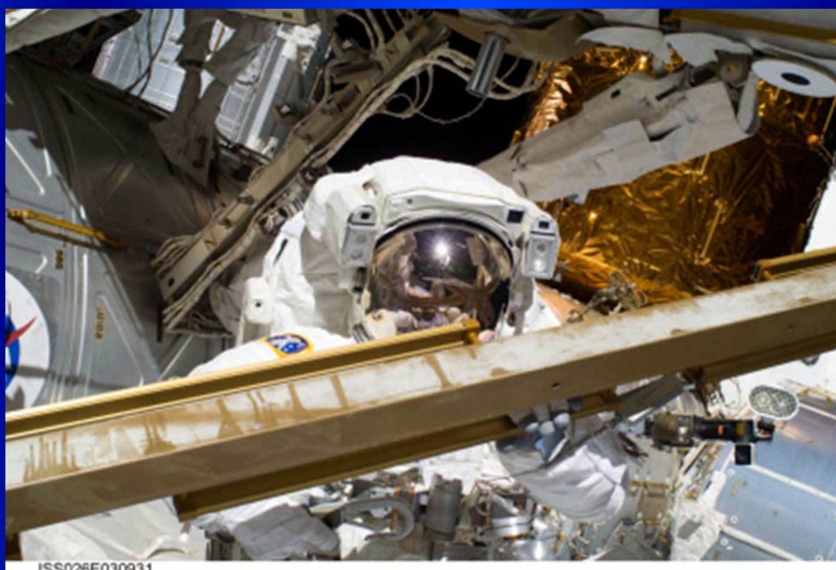
- Charged Particle Radiation
  - Radiation Belts
  - Auroral Region
  - Solar Wind
  - Interplanetary

Contamination

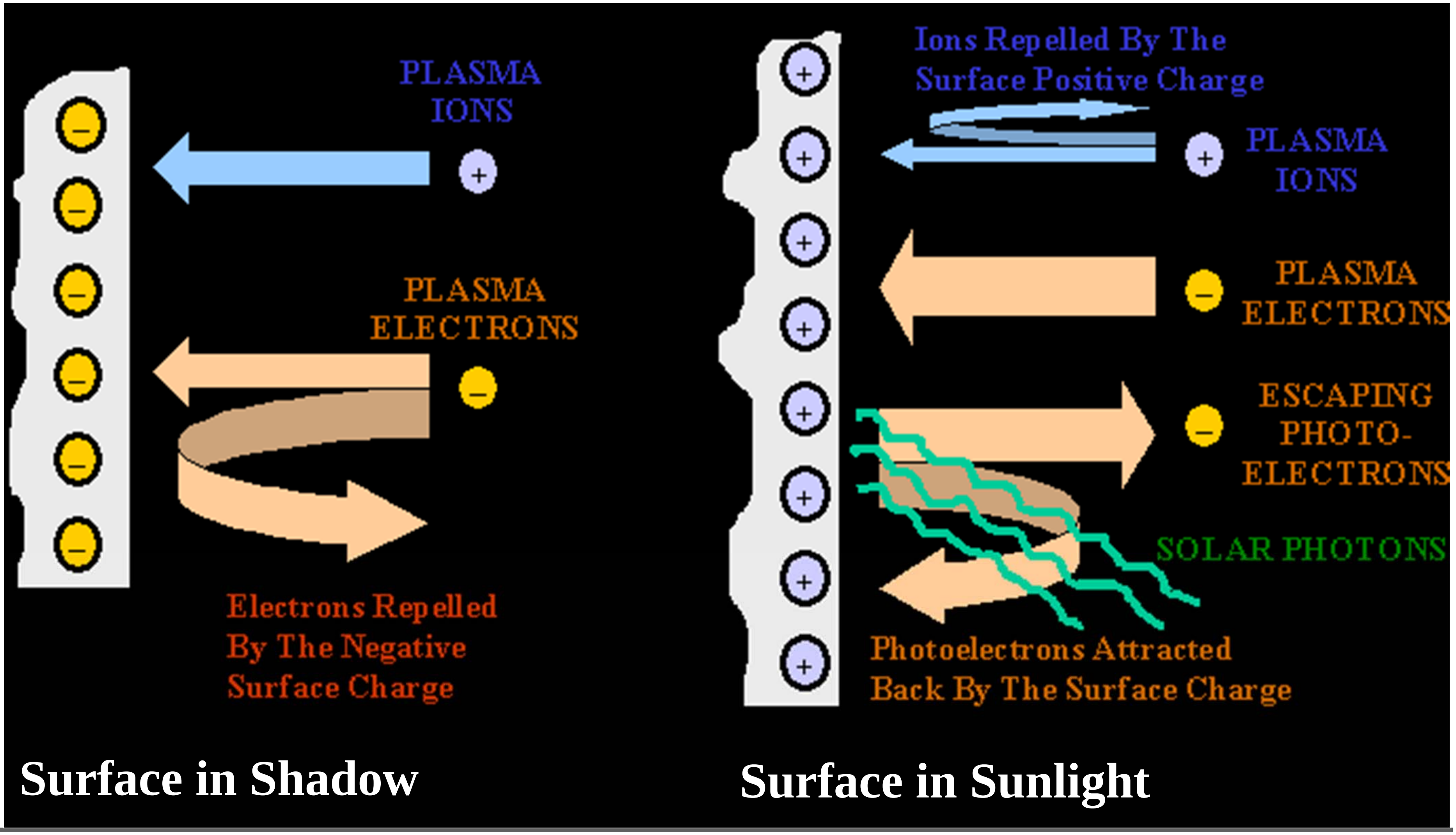
- **Particulate and Molecular**
  - **Particulate Contamination Generated by Handling, Launch Vibration, AO, Moving Parts…**

  - **Volatiles may Escape Materials due to Outgassing in Space, Venting, Engine Firing…**
    - **Outgassing Rate is Temperature Dependent**
    - **Deposition on other spacecraft surfaces**
    - **Deposition Rate Affected by Solar UV, AO, and Surface Temperature**

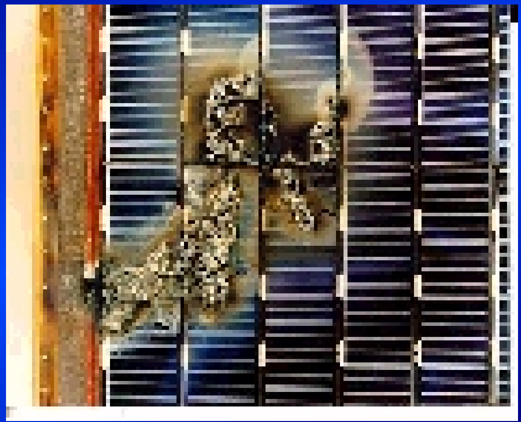




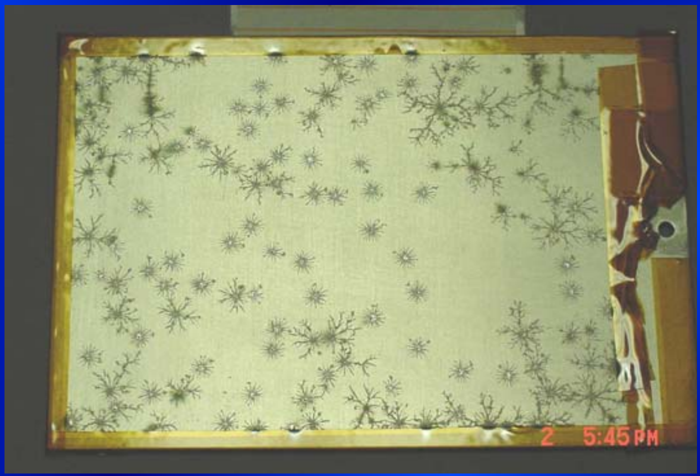
- Contamination Control
  - Contamination Control Imperative for Sensitive Optics and Thermal Control Surfaces
  - Ground Support Equipment is Considered a Potential Contamination Source
  - Standard Material Tests and Modeling for Contamination Exists
    - Databases of Materials are Maintained
  - Contamination Control can be Achieved
    - Material Selection, Thermal Vacuum Bake-out, Clean Room Control, Spacecraft Design


PLASMA
IONS
PLASMA
ELECTRONS
Electrons Repelled
By The Negative
Surface Charge
Surface in Shadow
Ions Repelled By The
Surface Positive Charge
PLASMA
IONS
PLASMA
ELECTRONS
ESCAPING
PHOTO-
ELECTRONS
SOLAR PHOTONS
Photoelectrons Attracted
Back By The Surface Charge
Surface in Sunlight

- Spacecraft can Interact with Ambient and Induced Plasma Environments
  - High Voltage Solar Arrays can be Damaged by Arcing
  - Floating Potentials can Charge Spacecraft Leading to Damage on Surfaces
    - Dielectric Breakdown, Contamination from Ejecta, Sputtering due to Ion Impact
  - Currents Collected by Arrays Flow in Structure



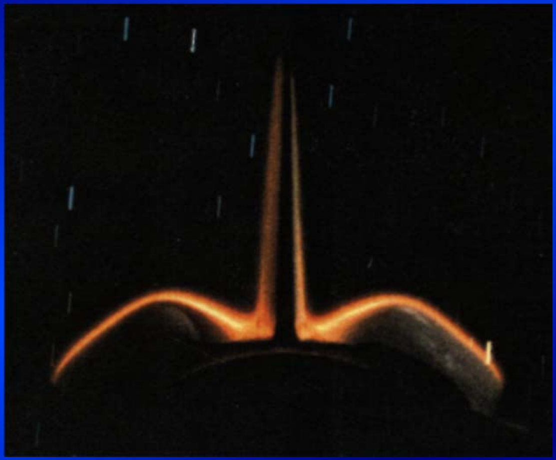
Solar Array Arc

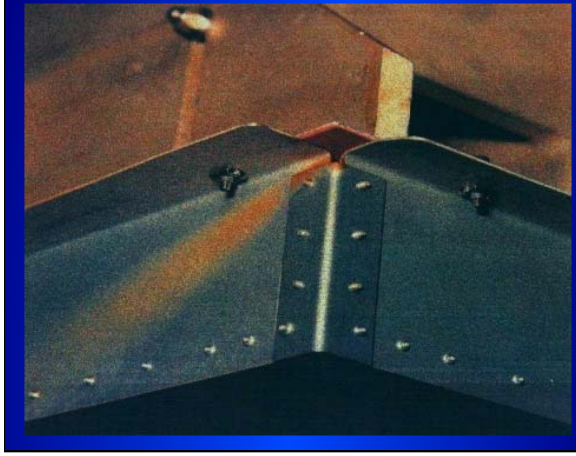


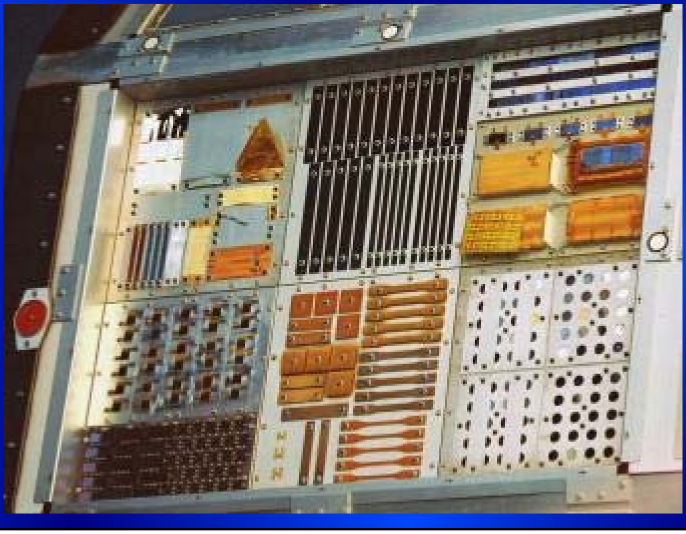
Dielectric Breakdown in Anodize Aluminum

Atomic Oxygen (AO)

- The Main Constituent at 200-500 Km is AO
  - The AO Density Decreases Exponentially with Altitude
  - Spacecraft Velocity > Thermal Velocity means that AO Impacts Ram Facing Surfaces with ~ 5eV
  - AO Erodes many Polymeric Materials
    - Mass Loss Affects Thermal, Optical and Mechanical Properties
    - AO Oxidizes Metallic Materials
  - AO Interaction with Exterior Materials can Produce Glow
  - AO Interaction can Enhance Contaminant Deposition

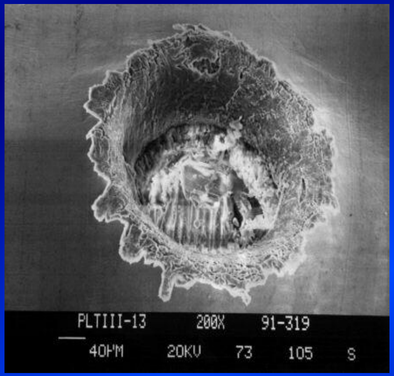


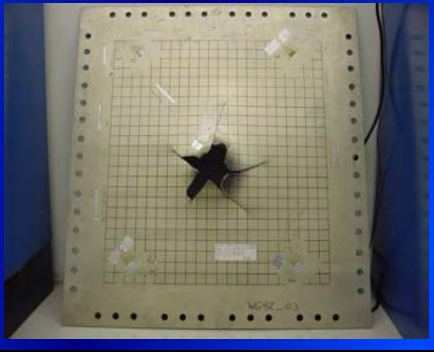




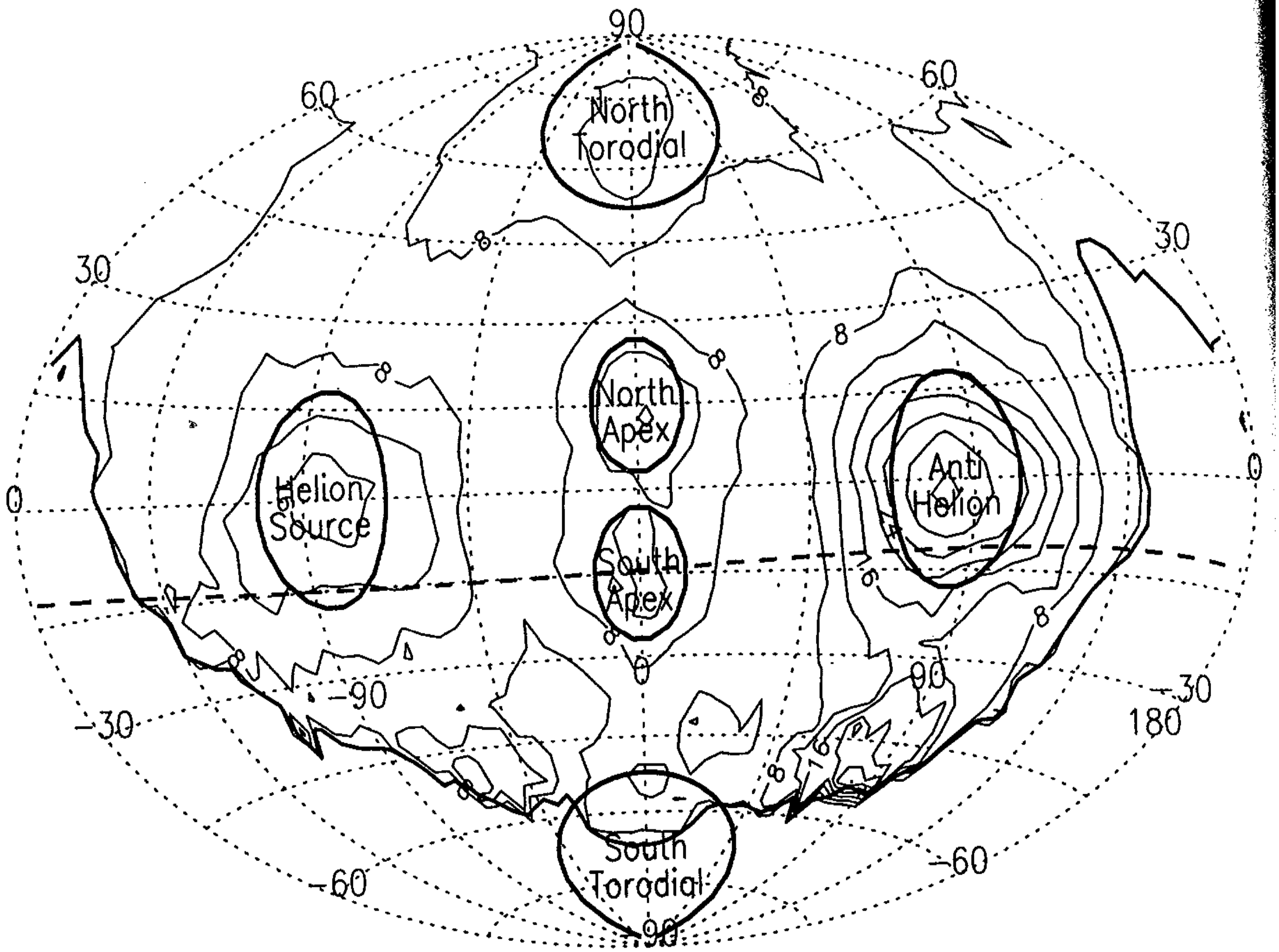
- Degradation of Material Properties
  - **Causes Darkening of Materials such as Silica Glass, Thermal Control Coatings, Polymer Films, Some Composites and Ceramics**
  - **Embrittlement of Polymer Films**
  - **Thermal Control Properties may be Seriously Degraded by UV Exposure of Contaminants Adsorbed onto Surfaces**
    - **Simultaneous UV and Contaminant Flux to a Surface can Significantly Enhance Permanent Contaminant Deposition**

- Naturally Occurring Particles are Meteoroids, Man-Made Particles are Orbital Debris
  - **Average Velocity of 17 Km/s for Micrometeoroids and 8 Km/s for Orbital Debris**
    - **Models of Environment Exist and Probability of Impact can be Calculated**
    - **Impacts can Penetrate Walls, Cause Pitting of Optics, Degrade Solar Arrays, and Thermal Control Materials**

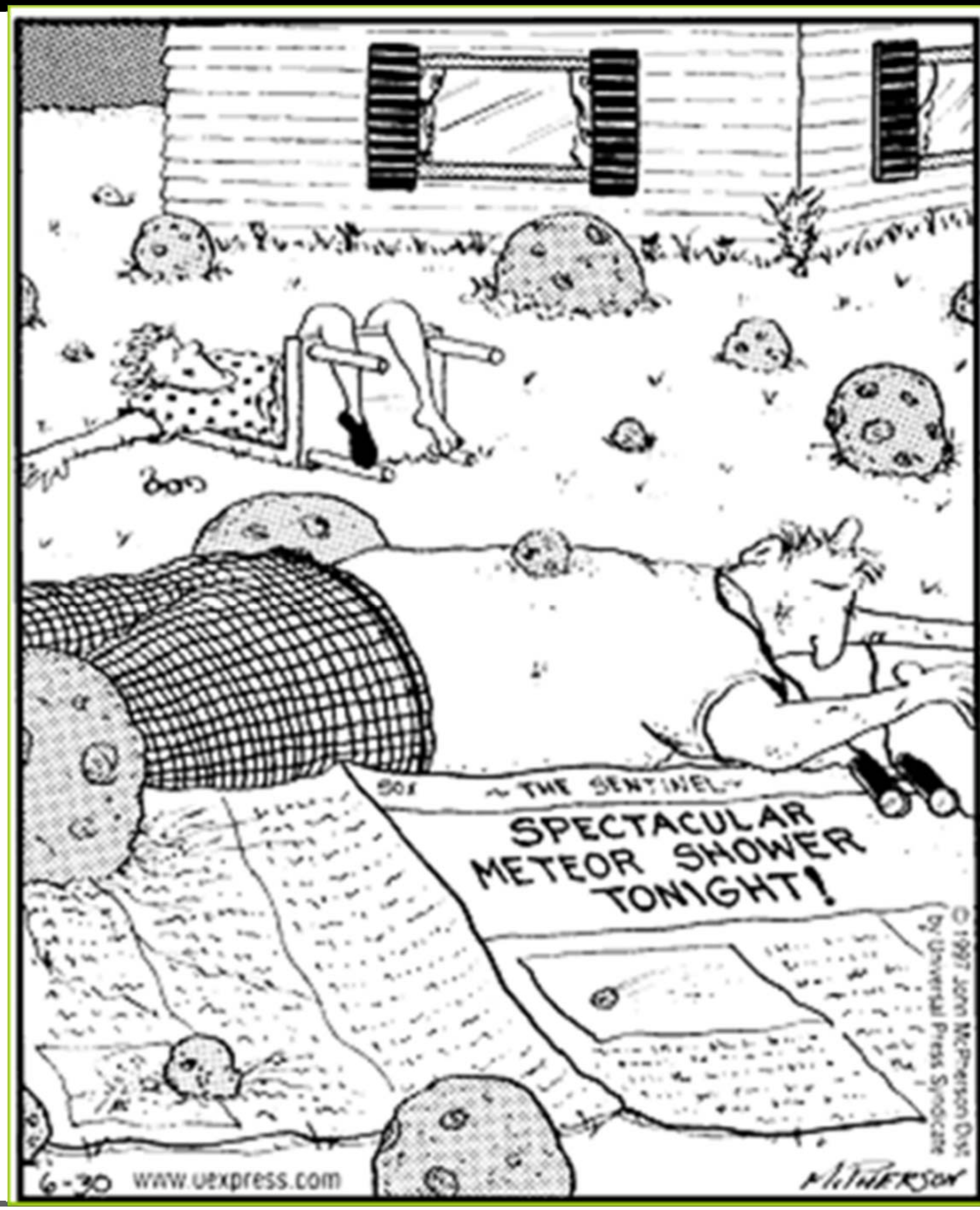




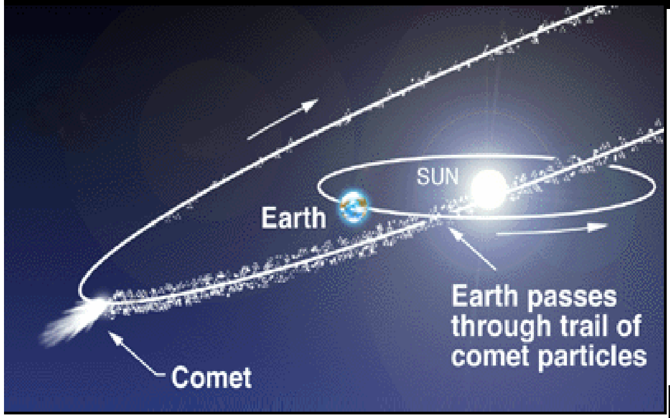
Environments - Sporadic Meteoroids



Environments - Meteoroids



Environments - Meteoroid Streams



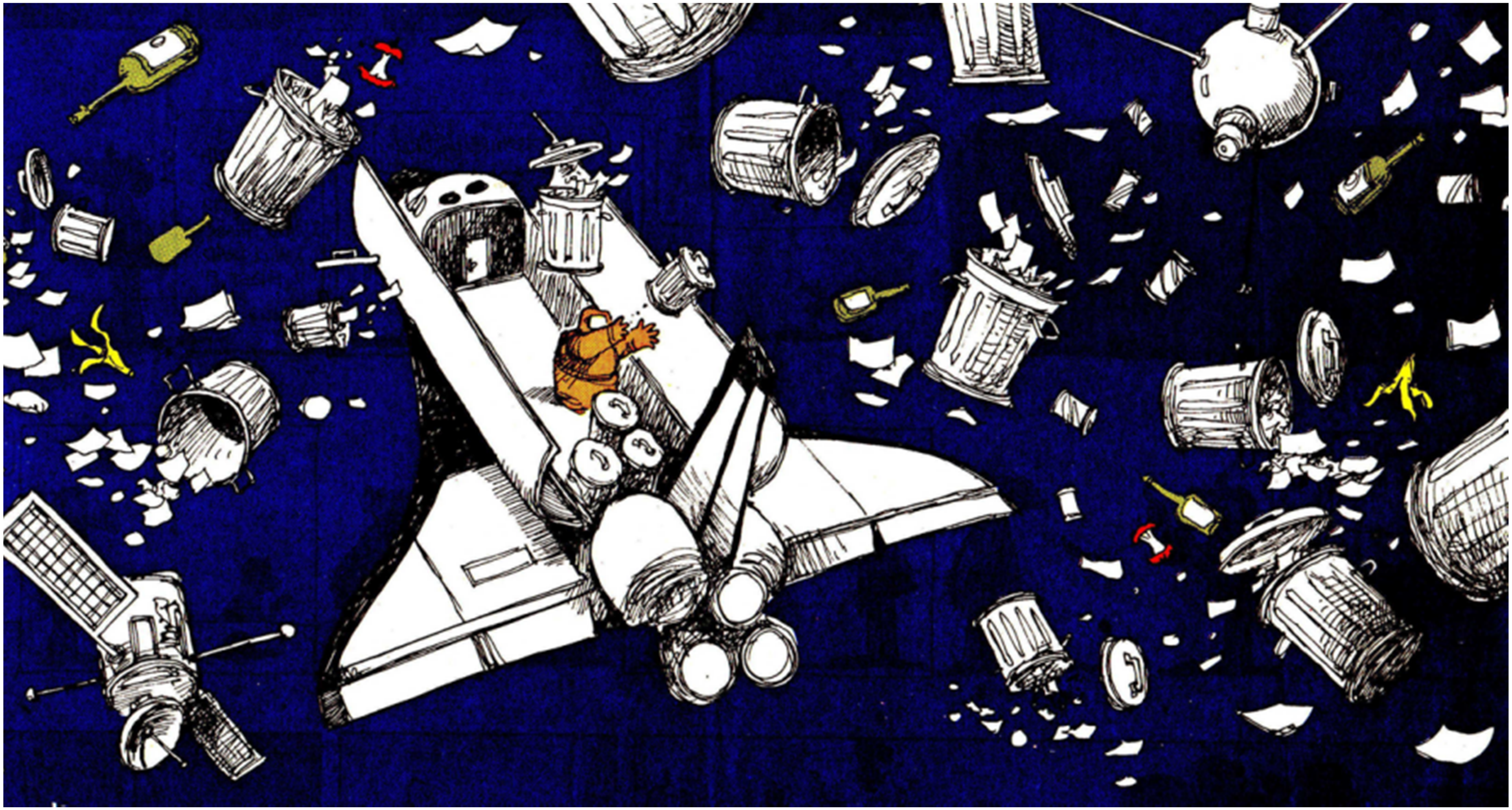
- Consist of particles ejected from the parent comet during a single passage around the Sun.
- Produce meteor showers and storms here on Earth.

Over time

- slight differences between the comet's and particles' velocities
- perturbations caused by planetary gravity and solar radiation pressure change the orbit of the stream so that it no longer follows the exact path of the comet.

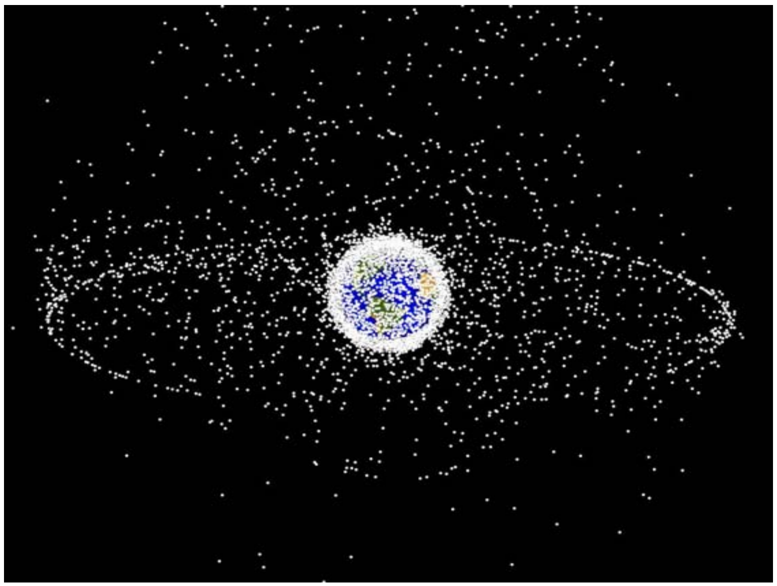
Shower	Peak	RA	Dec.	Duration (days)	Rate (/hr)
Quadrantids	Jan. 3	231	+50	0.5	90
Lyrids	Apr. 21	272	+32	2	5
Eta Aquarids	May 4	336	00	10	30
Northern Delta Aquarids	July 29	339	00	20	10
Perseids	Aug. 12	46	+58	5	70
Orionids	Oct. 21	95	+15	5	20
Taurids	Nov. 1	54	+21	30	5
Leonids	Nov. 16	152	+22	4	5
Geminids	**Dec. 13**	**113**	**+32**	**6**	**100**
Ursids	Dec. 22	217	+80	2	15

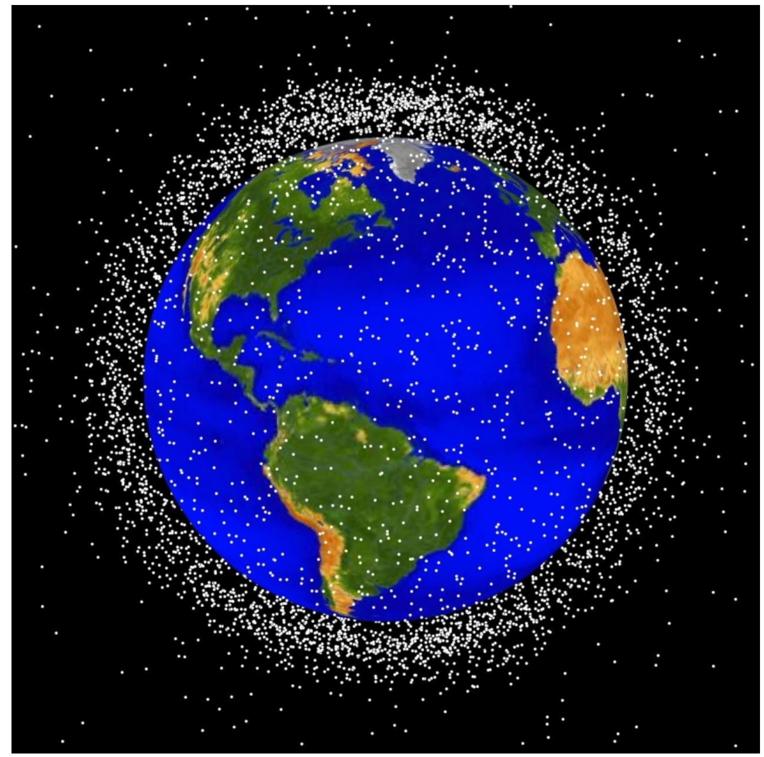
Environments – Orbital Debris

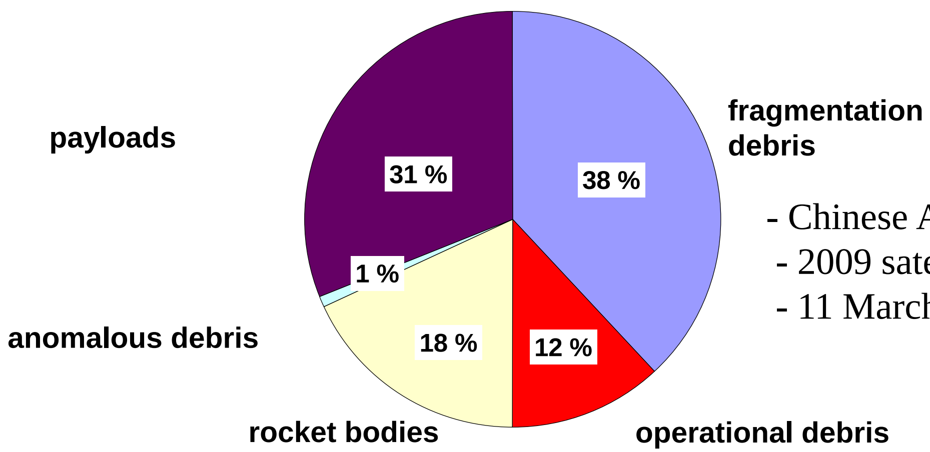


Environments – Orbital Debris

~19,000 tracked
(≥5 cm diameter)





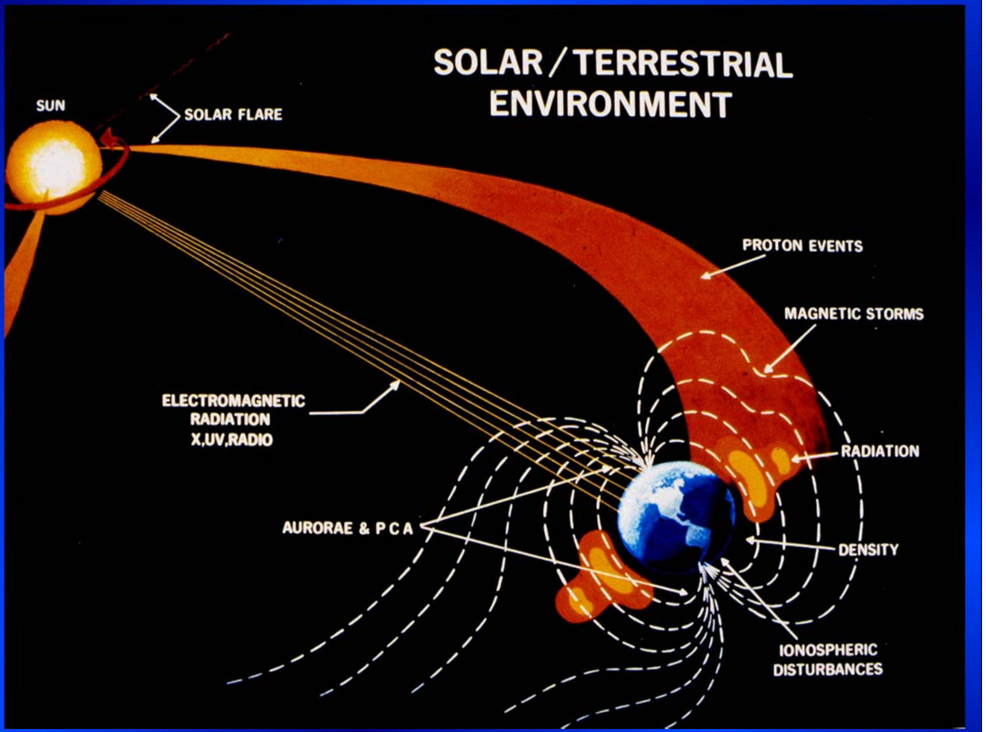


- Chinese ASAT test FENGYUN 1C in 2007
- 2009 satellite collision between Iridium 33 and Cosmos 2251
- 11 March 2000, a Chinese Long March 4 upper stage exploded in orbit

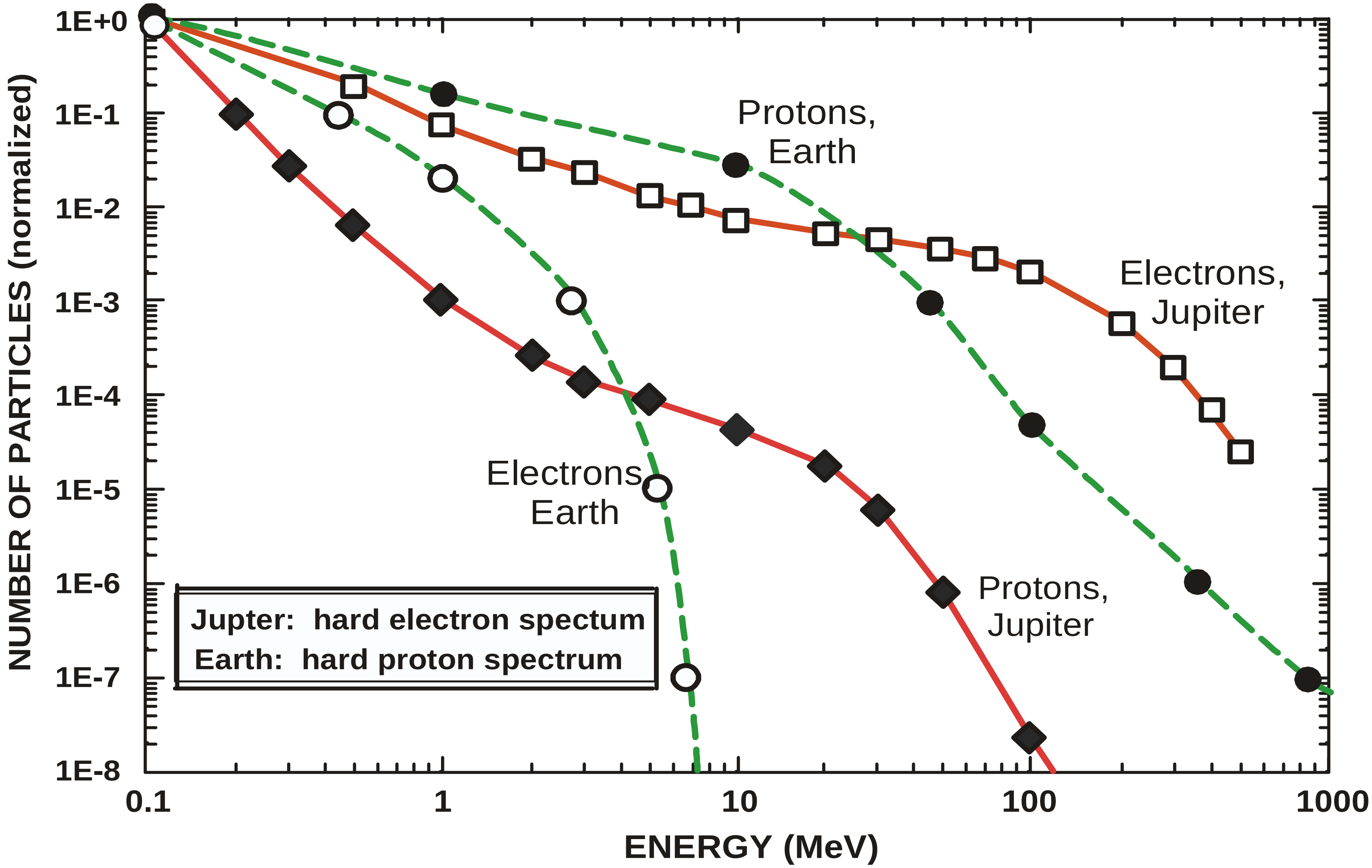
Courtesy NASA JSC, M. Matney, J.C. Liou

Radiation Environment

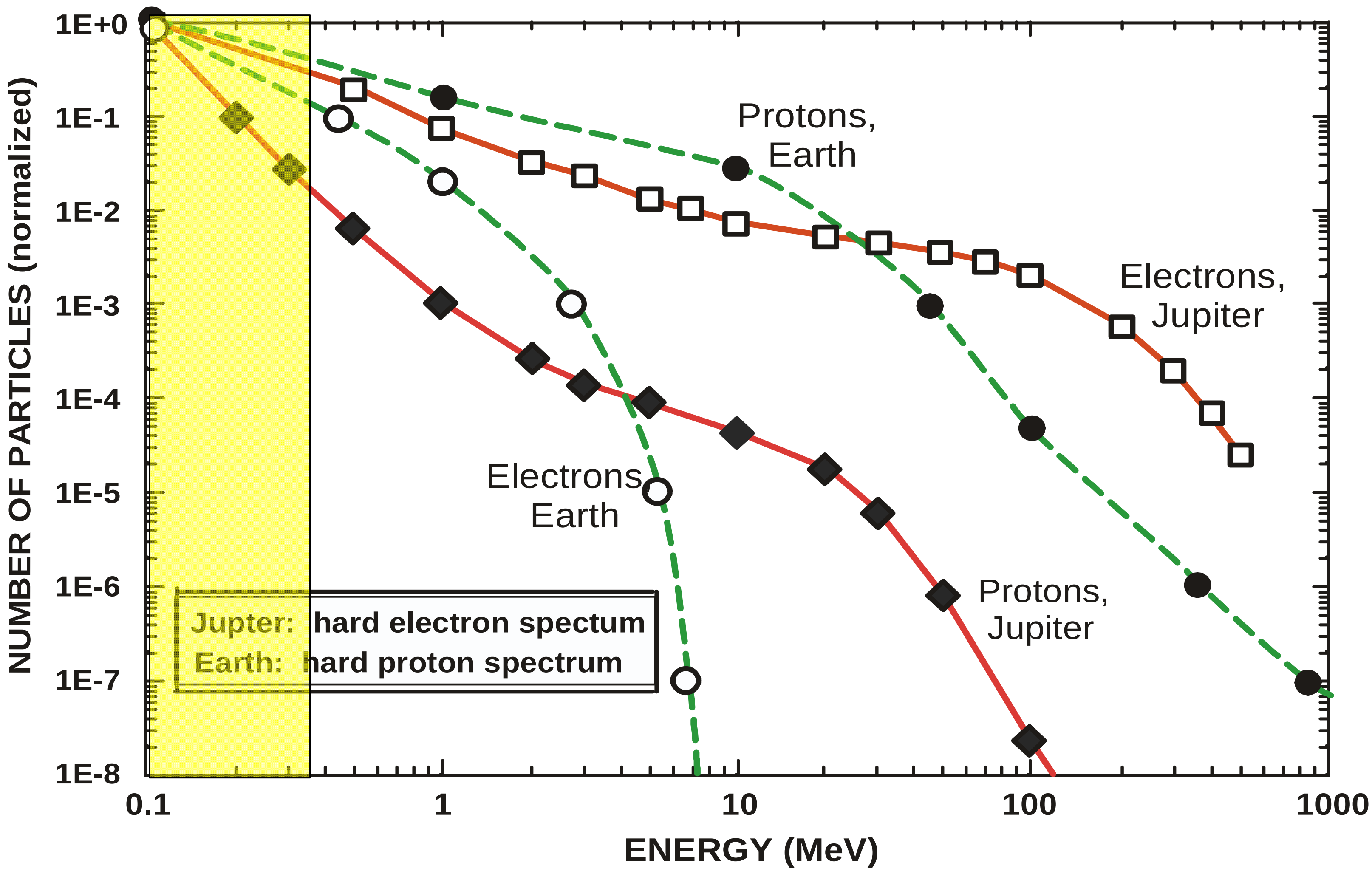
- Particle Radiation Displaces atomic Structure and Ionizes Material in its Path
  - **Result is Degradation in Material Properties**
  - **Cross-Linking (Hardening) and Chain-Scission (Weakening) of Polymers**
  - **Degradation of Solar Cell performance**
  - **Single Event Upsets (SEU) in Avionics**
  - **Latch-up in Avionics**
  - **Total Dose damage in Avionics**
  - **Darkening of material**



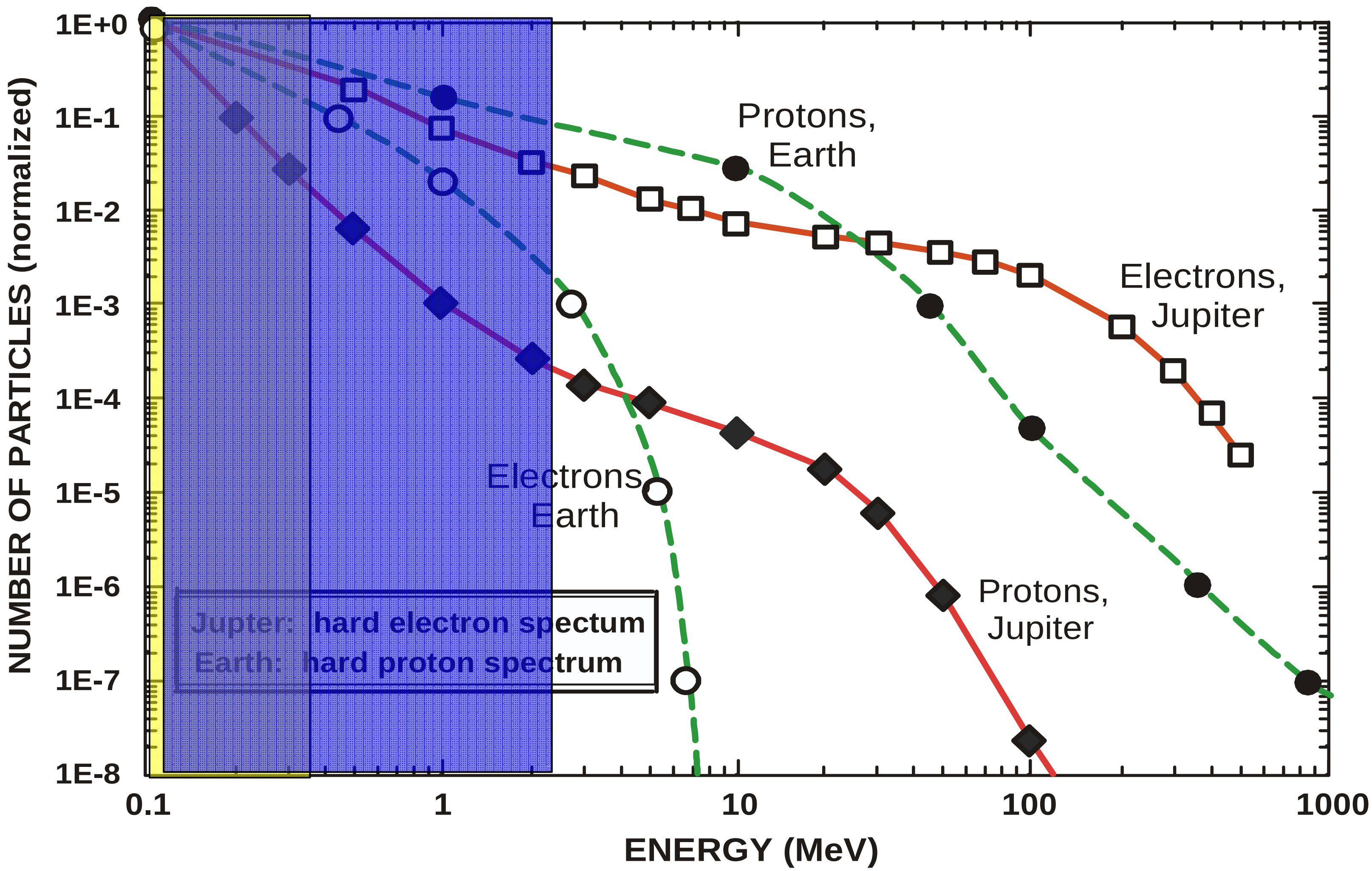
Comparison of the Earth and Jovian Radiation Environments



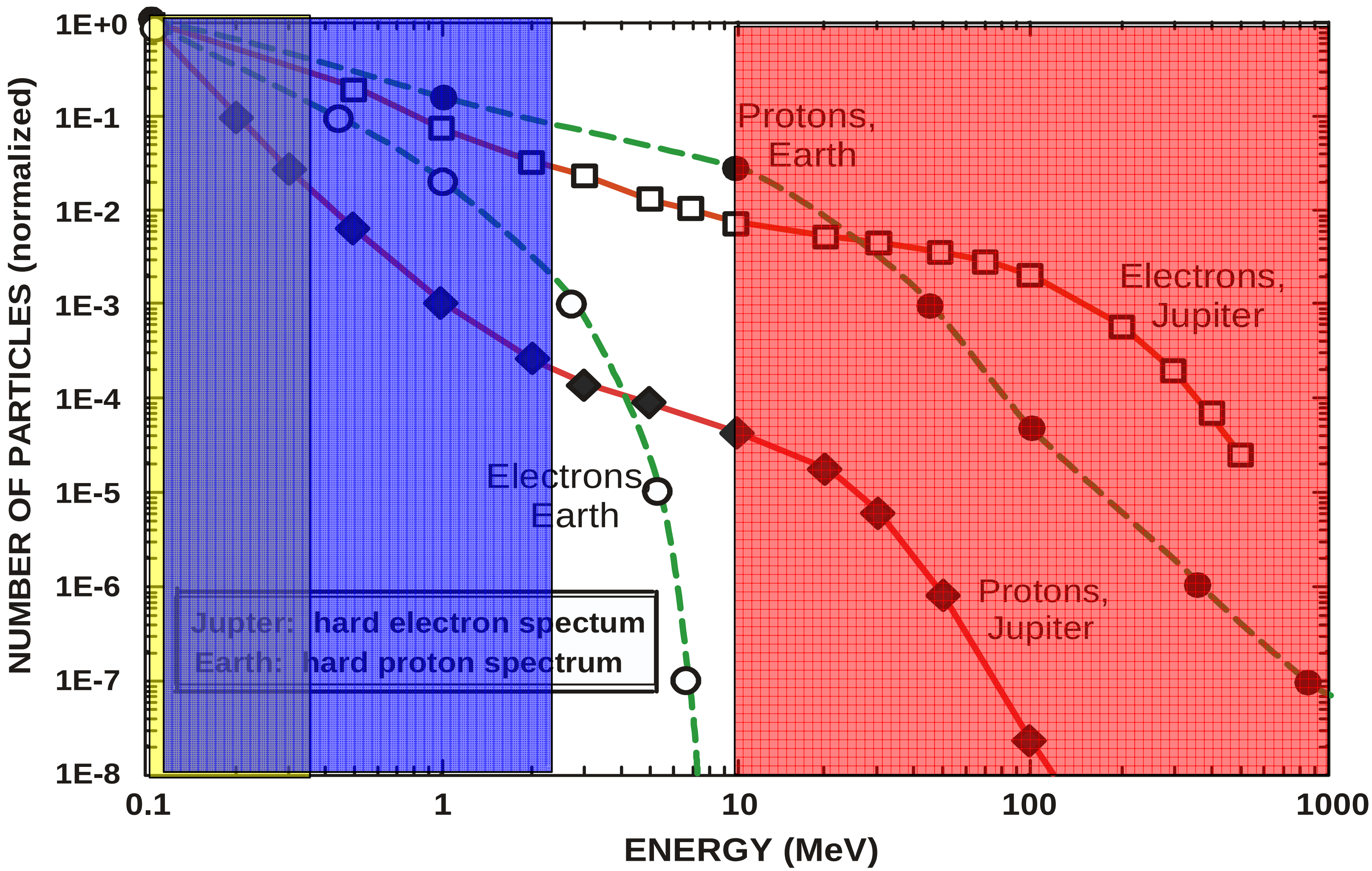
Comparison of the Earth and Jovian Radiation Environments



Comparison of the Earth and Jovian Radiation Environments



Comparison of the Earth and Jovian Radiation Environments



Mariner IV

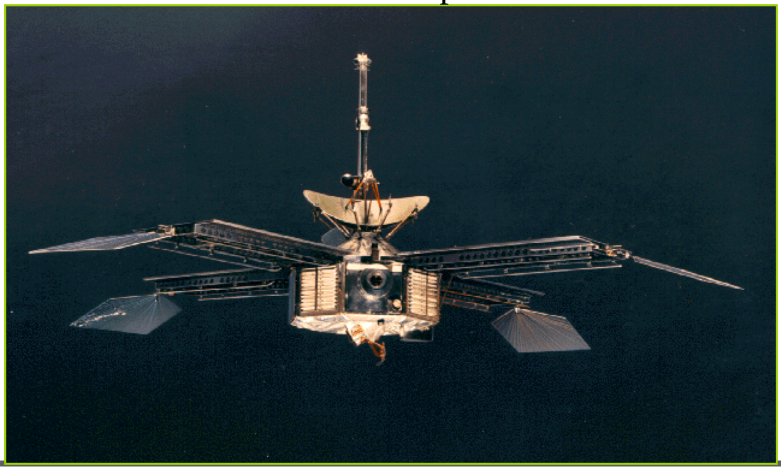
What: NASA planetary exploration spacecraft.

Event: Encountered meteoroid stream between the orbits of Earth and Mars in September 1967.

Consequences:

- Cosmic dust detector registered 17 hits within 15 minutes;
- 2-3 orders of magnitude more hits estimated over entire craft.
- Bombardment caused temporary change in attitude but no loss of power; torqued about the roll-axis.
- One-degree temperature drop indicative of thermal shield damage.

Outcome: Resumed normal operation within ~1 week.



Chandra X-Ray Observatory

What: NASA observatory.
Event: Struck by a Leonid or sporadic(?) near the time of Leonid shower peak in November 2003.

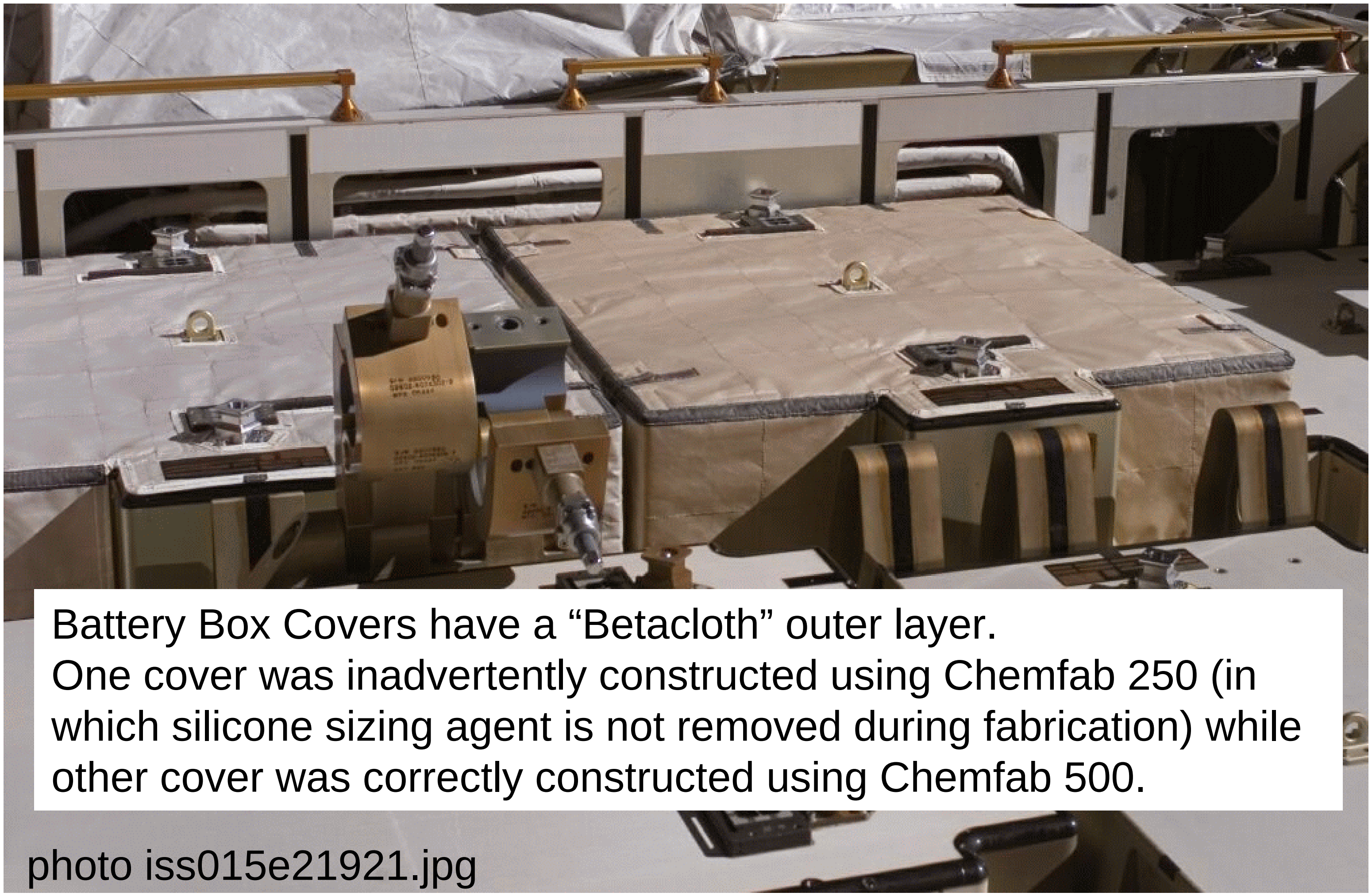
Consequences:

- Pointing stability discrepancy indicated strike, as no evidence of spurious thruster firings or an indication of an internal cause.
- Change in momentum – caused a "wobble".

Outcome: All systems continued to operate normally following the event.

External Surface Changes on ISS

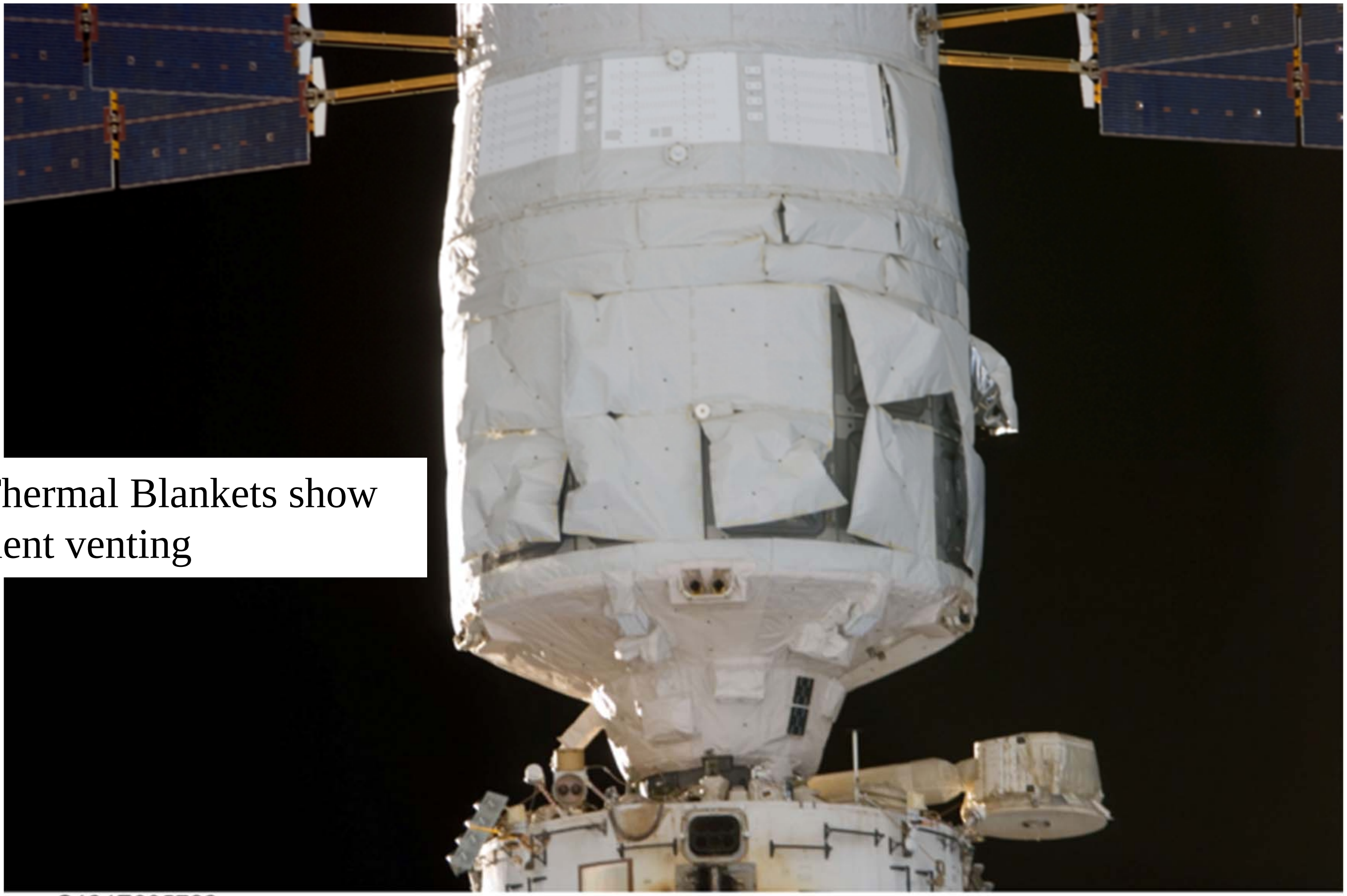
Inadvertent Materials Substitution + SEE



Battery Box Covers have a “Betacloth” outer layer.
One cover was inadvertently constructed using Chemfab 250 (in which silicone sizing agent is not removed during fabrication) while other cover was correctly constructed using Chemfab 500.

photo iss015e21921.jpg

Basic Materials Design + SEE



ATV1 Thermal Blankets show insufficient venting

S124E005722

External Surface Changes on ISS

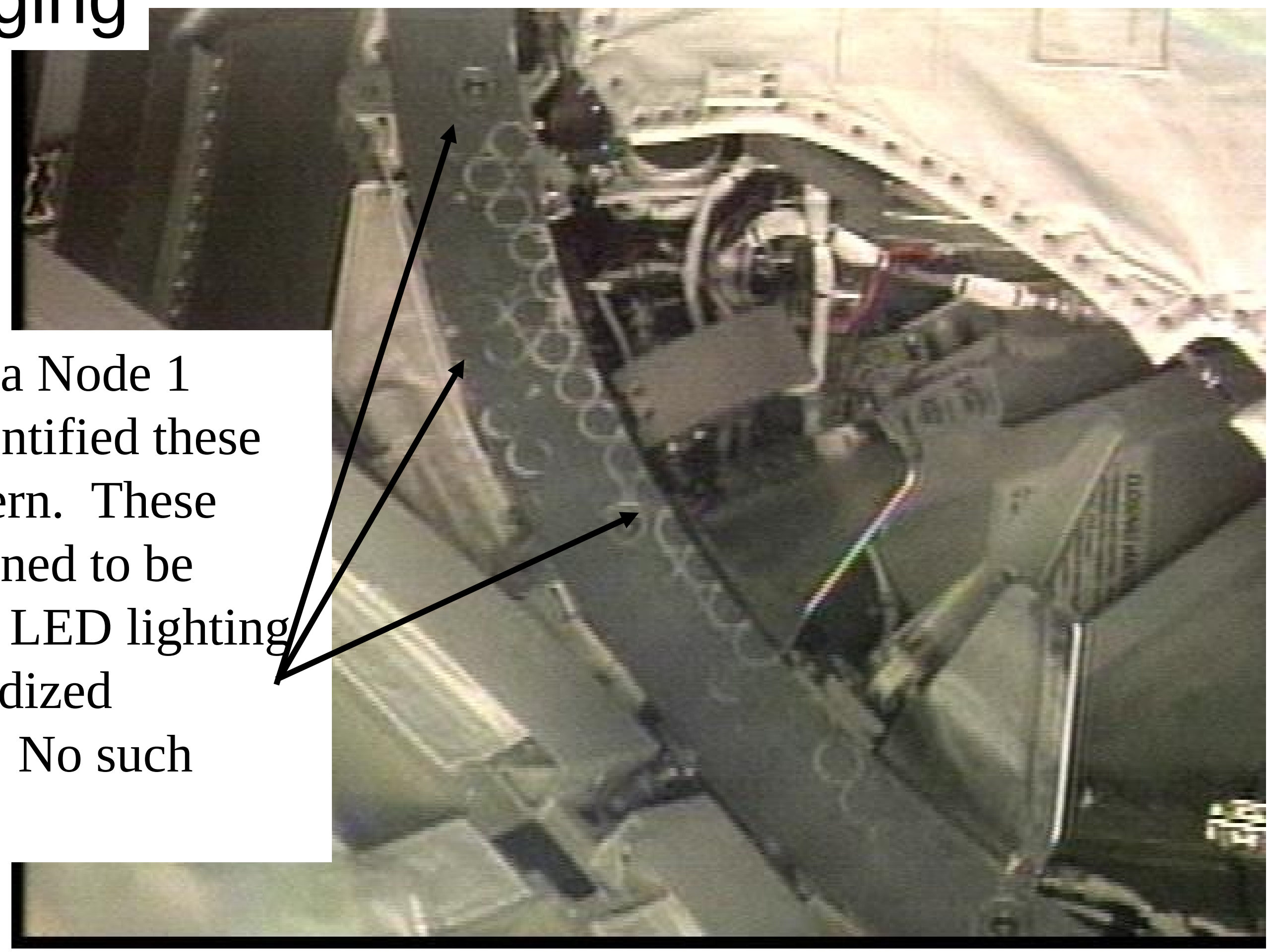
Space Environmental Effects – Frequent and “New” Visiting Vehicles

Soyuz docked to FGB
Outgassing or Thruster Contamination

ISS022E067004

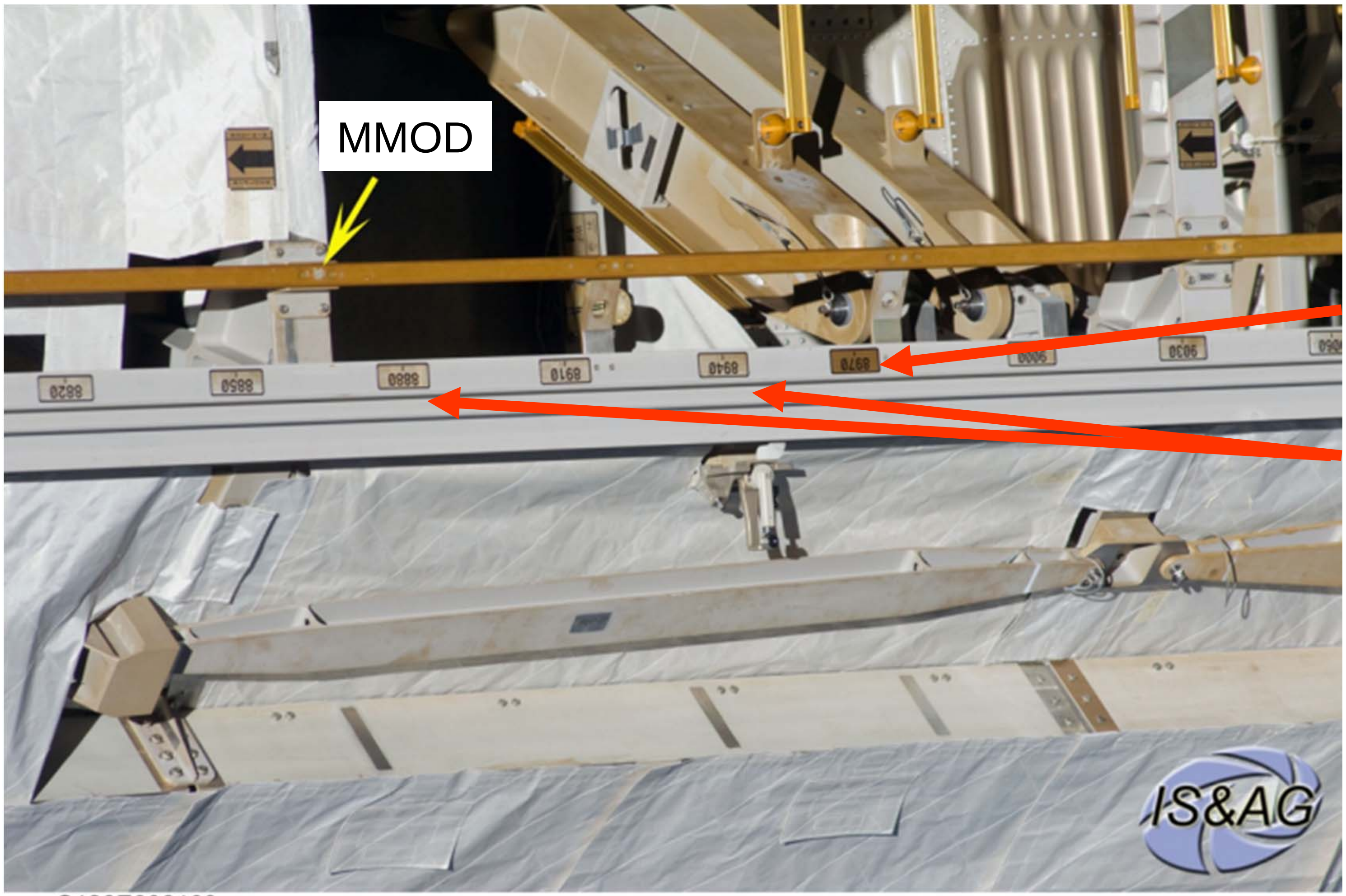
External Surface Changes on ISS

Issues with Imaging



Pre-berthing inspection of a Node 1 sealing surface in 2001 identified these circular features as a concern. These features were later determined to be reflections of the camera's LED lighting system on the smooth, anodized aluminum sealing surface. No such feature actually exists.

External Surface Changes on ISS



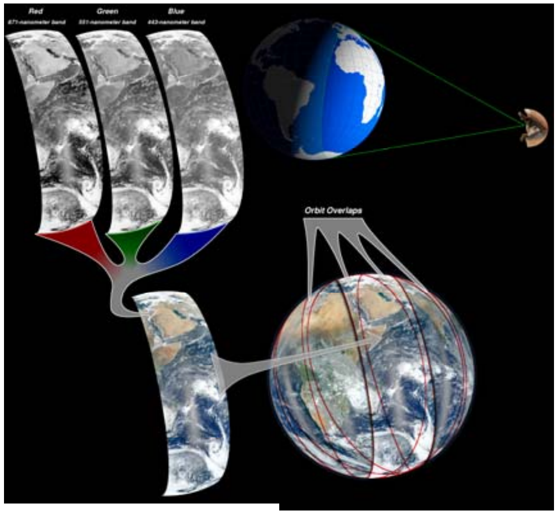
S128E008103

Anodized aluminum labels, which darkened quickly, have begun to recover their expected appearance with continued AO exposure!

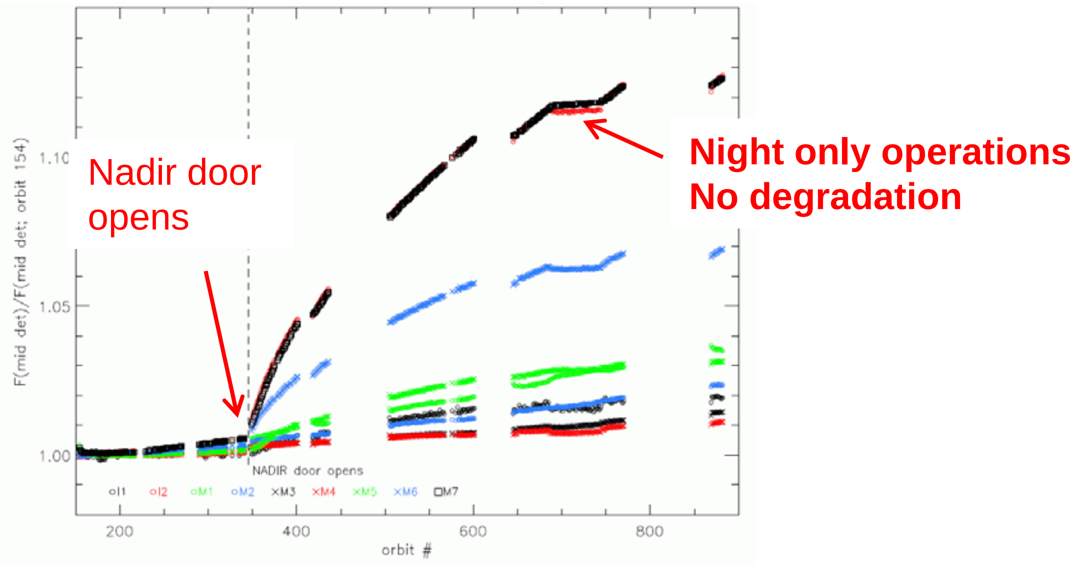
ISS Observations

- Some worse-than-expected materials degradation effects have been observed on ISS, but only one has created an operational issue (during P6 redeploy) and some surfaces (as with the anodized aluminum labels) appear to be recovering.
- Inadvertent materials substitutions have been observed, but none have created any operational issues.
- Hardware handling contamination effects have been observed, and although none have created operational issues, there is clearly room for improvement in this regard.
- Even with robust materials selections, space environmental effects will be observed.
- Be cautious when interpreting photography, as lighting conditions and the environment affect interpretation.

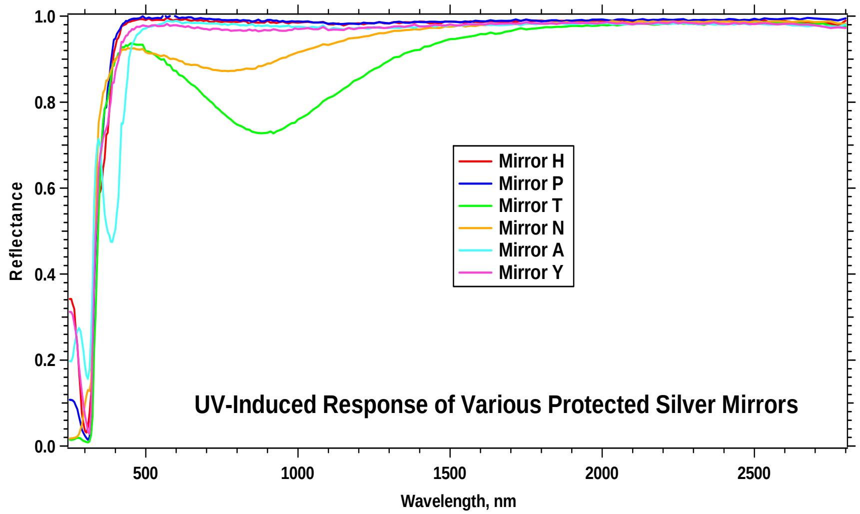
Visible Infrared Imaging Radiometer Suite (VIIRS)

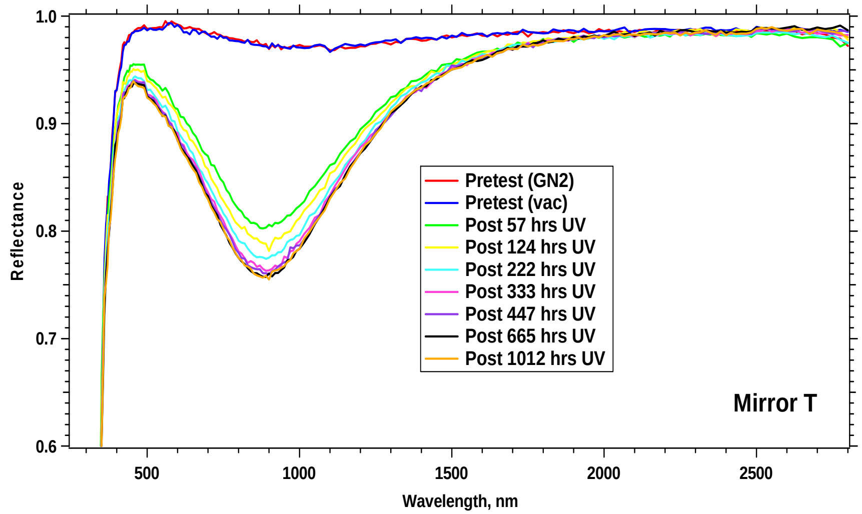


- Visible/infrared imaging radiometer suite (VIIRS)
    - 10 Silver mirrors
    - Dichroics separate the beam into:
        - Vis/NIR (10 bands)
        - Reflective IR (8 bands)
        - Thermal IR (4 bands)
- Radiometric calibration required for science missions
    - Once each orbit, sunlight illuminates diffuser material
- On-orbit data suggests most likely cause is UV-induced degradation of the telescope mirrors
  - Mirrors coated in 2004
  - Coating has extensive flight heritage
- Root-cause hypotheses proposed:
  - Inherent coating defect
  - Contamination prior to launch
  - Contamination after launch



VIIRS Space System Anomaly





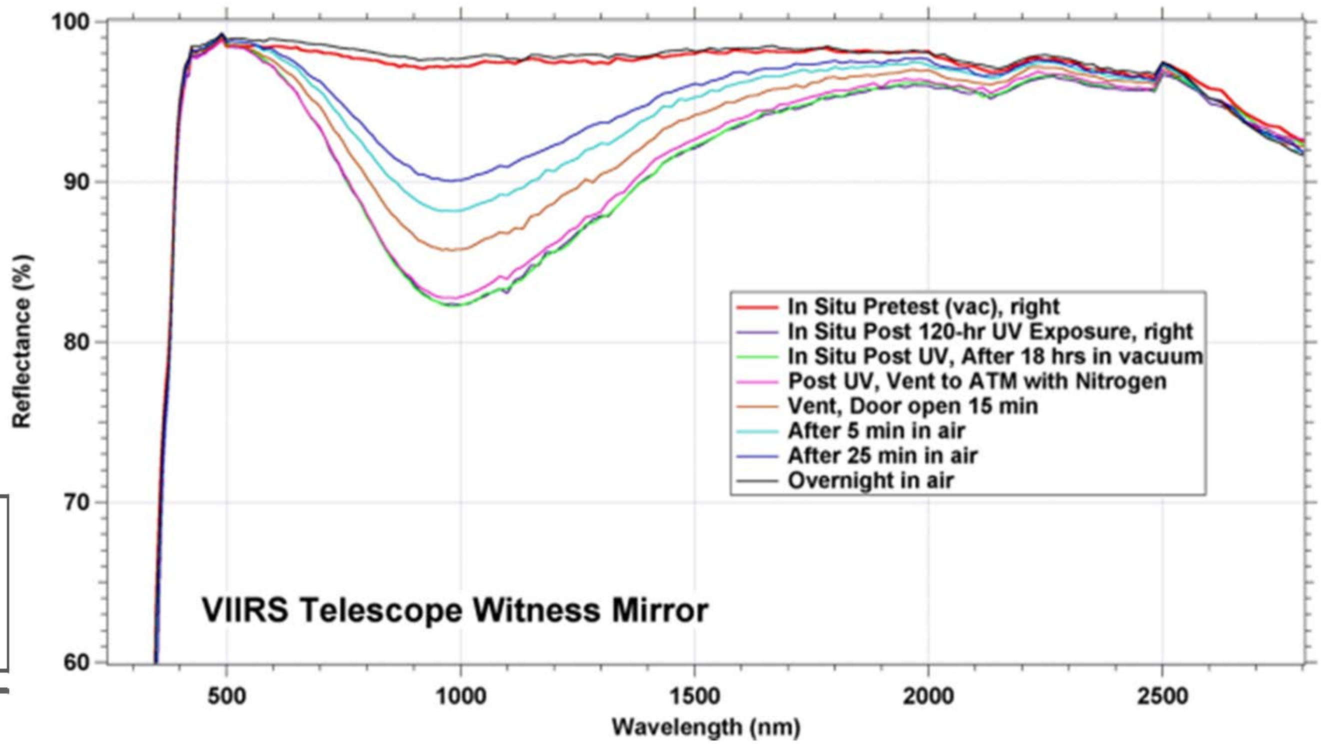
- UV and/or electron radiation can induce absorptions in protected silver mirrors.
- Tests on a variety of mirror types yielded varying results - susceptibility depends upon materials/processes used.
- These results were reported to the program in 2005, but was considered a low risk for their flight-proven coating - ***did not pursue testing*.**

- **TWM-Telescope Witness Mirror was made in the same mirror deposition run as the flight mirrors, saw Assembly Integration and Test environment**
- **CFM1- Contractor Furnished Mirror- was made in the same mirror deposition run as the flight mirrors, but stored in pristine conditions**
- **A3-31- The same type of mirror, but made at a different time and stored in pristine conditions.**
- **CERES mirror- A different type of mirror that was attached to a different instrument during Assembly Integration and Test**

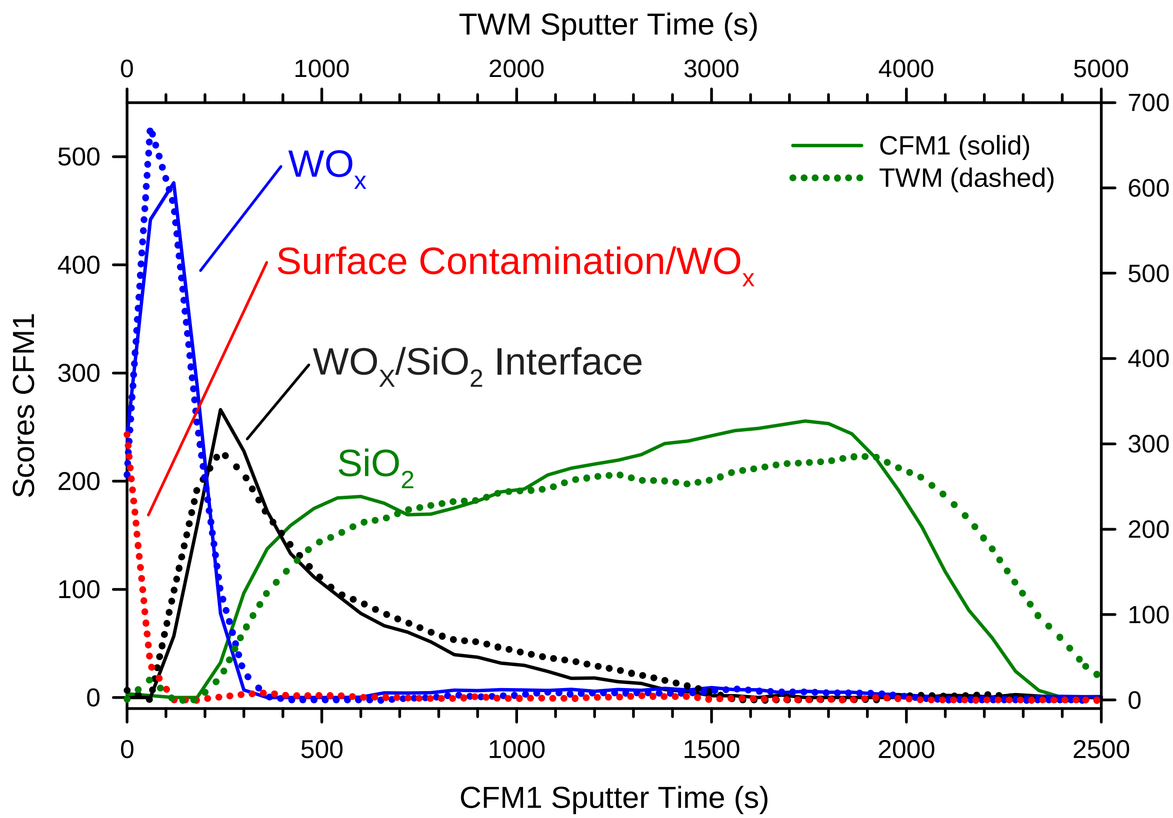
- Control Materials
  - 2-mil Rear-Surface-Aluminized Kapton
  - 2-mil Rear-Surface-Silverized Teflon (AgFEP)
  - Z93-P White Paint

- Contamination Monitors
  - Vapor Deposited Aluminum (VDA) Front-Surface Mirror
  - 7980 Fused Silica
  - Polished Silicon Wafer

Samples were exposed to Xe illumination equivalent to 1-sun intensity.



A3-31 Mirror of the same design as Flight mirrors but produced in a different coating run, was unaffected by the UV exposure.



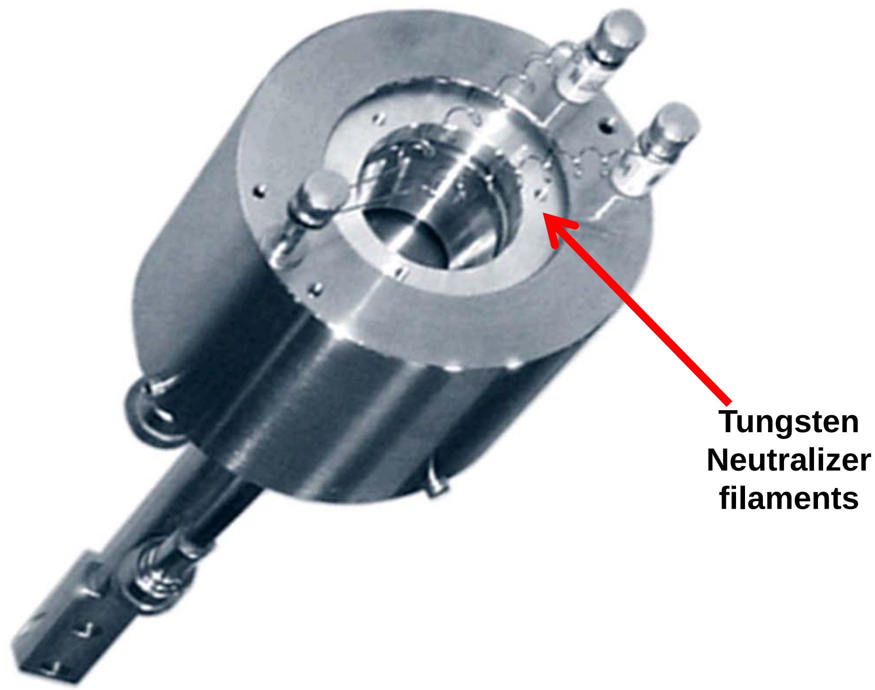
VIIRS on-orbit degradation likely due to UV-induced darkening of Tungsten Oxide on RTA mirrors

- **UV-induced degradation of tungsten oxide contaminated witness mirrors (TWM, CFM1) from the Flight (RTA) coating run**
- **Uncontaminated witness mirrors from other coating runs did not respond to UV exposure.**
- **WO_{3-x} is a known photochromic and electrochromic material. Loss of oxygen induces a strong near infrared absorption.**

- After discovery of tungsten oxide on the surface of TWM, the vendor's coating records were reviewed.
- Vendor explained that the coating process includes cleaning substrates (prior to deposition) using an oxygen ion source.
  - Oxygen ion source possesses Tungsten neutralizer filaments
    - Explains tungsten oxide at coating/substrate interface
  - *The ion source remains off during the coating process*
- Rotating Telescope Assembly (RTA) mirrors initially exhibited low reflectance, thought to be due to a lack of oxygen in the top dielectric layer of coating.
  - The delivery of these completed mirrors was already behind schedule…

The Smoking Gun

- Proposed using the oxygen ion source to further oxidize top-coating
- Unqualified process - tested once on a single witness sample
- Not discussed with program's subject-matter experts
- Process was hastily implemented (on a Sunday)
- No further testing of witness samples was considered



Travelling witness samples are very valuable!

Summary

- Define the environment
- Be aware of the combined environmental effects: Synergisms
- Test materials and systems to ensure engineering performance is well above end of life requirements at the end of mission
- Literature search/appropriate flight heritage can save time and lower cost
- Flight heritage in one environment does not qualify for use in another environment
- Processes need to be fully qualified - and *strictly followed*
- Schedule pressures should not induce process deviations
- Changes need to be discussed with all stakeholders
- Beware unintended consequences of creative solutions
- Even good ideas need to be tested and verified
- Even with robust materials selections, space environmental effects will be observed.
- Test as you fly (and fly as you test) - ensure that test specimens are fully representative of the flight article and test environments are representative of flight.

***** Ground-based testing remains a key facet of mission assurance**

Thank You for your Time

Space Environments and Interactions References

BASIC CONCEPTS

- Haymes, R.C. Introduction to Space Science. New York, NY: John Wiley and Sons, Inc., 1971.
- Garrett, H.B. and C.P. Pike, eds. "Space Systems and Their Interactions with Earth's Space Environment." Prog. Astronaut. Aeronaut. 71 (1980):
- Jursa, A., ed. Handbook of Geophysics and the Space Environment. National Technical Information Services Document, Accession No. ADA 167000, 1985.
- Wertz, J.R. and W.J. Larsen, eds. Space Mission Analysis and Design. Doredecht, The Netherlands: Kluwer Academic Publishers, 1991.
- DeWitt, R.N., D.P. Dutson, and A.K. Hyder, eds. The Behavior of Systems in the Space Environment. Doredecht, The Netherlands: Kluwer Academic Publishers, 1994.
- Tribble, A. The Space Environment: Implications for Spacecraft Design. Princeton, NJ: Princeton University Press, 1995
- Hastings, D., and H.B. Garrett. "Spacecraft-Environment Interactions." Atmospheric and Space Science Series, ed. A.J. Dessler. Cambridge, England: Cambridge University Press, 1996.

SPACE ENVIRONMENTS AND INTERACTIONS REFERENCES

ENVIRONMENTS

Sun

Feynman, J. "Solar Wind." Chap. 3 Handbook of Geophysics and the Space Environment, Springfield, VA: National Technical Information Service, ADA 16700, 1985.

Feynman, J., G. Spitale, J. Wang, and S. Gabriel. "Interplanetary Proton Fluence Model: JPL 1991." J. Geophys. Res. 98 (A8, August 1, 1993): 13,281-13,294.

Earth

Atmosphere

Whitten, R.C. and I.G. Poppoff. Fundamentals of Aeronomy. New York: J. Wiley & Sons, Inc., 1971.

Banks, P.M. and G. Kockarts. Aeronomy, Parts A and B. New York: Academic Press, 1973.

Whitten, R.C., W.W. Vaughn, K.S.W. Champion, and R. Reid. Guide to Reference and Standard Atmosphere Models. AIAA, 1996. American National Standard BSR/AIAA G-003A-1996.

Ionosphere

Carlson, H.C., D.N. Anderson, S. Basu, E.J. Fremouw, R.R. Heelis, and R.W. Schunk. Guide to Reference and Standard ionosphere Models. AIAA, 1999. American National Standard BSR/AIAA G-034-1998.

Magnetosphere

General

Alfven, H. and C.G. Falthammar. Cosmical Electrodynamics. Oxford: Clarendon press, 1963.

Garrett, H.B. "Review of Quantitative Methods of the 0 to 100 keV Near-Earth Plasma." Rev. Gepphys. Space Sci. 17 (1979): 397-416

Space Station Electromagnetic, Ionizing Radiation, and Plasma Environment Definition and Design Requirements. NASA Space Station Freedom Program Office, 1990. SSP 30420

Magnetic Field

Knecht, D.J. and B. Shuman. "The Geomagnetic Field." Handbook of Geophysics and the Space Environment, Springfield, VA: National Technical Information Service, ADA16700, 1985.

Langel, R.A. "IGRF, 1991 Revision." EOS Trans. AGU 73 (1992): 182

Tsyganenko. "A Model of the Cis-Lunar Magnetospheric Field." Annals. Geophys. 32 (January-March 1976): 1-12.

Plasma Dynamics

Roederer, J.G. Dynamics of Geomagnetically Trapped Radiation. Vol. 2. Physics and Chemistry in Space, New York: Springer-Verlag, 1970.

Northrop, T.G. "The Adiabatic Motion of Charged Particles." Interscience, New York, NY: 1963.

Radiation Models

Vette, J.I. The AE-8 Trapped Electron Model Environment. NSSDC/WDC-A-R&S, 1991. 91-24

SPACE ENVIRONMENTS AND INTERACTIONS REFERENCES

Sawyer, D.M. and J.I. Vette. AP-8 Trapped Proton Environment for Solar Maximum and Solar Minimum. NSSDC/WDC-A-R&S, 1976. 76-06.

Brautigam, D.H., M.S. Gussenhoven, and E.G. Mullen. "Quasi-Static Model of Outer one Electrons." IEEE Trans. Nucl. Sci. 30 (39:(6) 1992): 1797-1803.

Lemaire, J.F., D. Heynderickx, and D.N. Baker. Radiation Belts Models and Standards. Vol. 97. Geophysical Monograph Series, Washington, D.C.: American Geophysical Union, 1996.

Daly, E.J., J. Lemaire, D. Heynderickx, and D.J. Rodgers. "Problems with Models of the Radiation Belts." IEEE Trans. Nuc. Sci. 43 (2, April 1996): 403-415.

Jupiter

Gehrels, N., ed. Jupiter. Tucson, AZ: University of Arizona Press, 1976.

Dessler, A.J., ed. Physics of the Jovian Magnetosphere. Cambridge Planetary Science Series. New York: Cambridge University Press, 1983.

Divine, T.N. and H.B. Garrett. "Charged particle distributions in Jupiter's magnetosphere." J. Geophys. Res. 88 (A9, Sept. 1983): 6889-6903.

Space Debris

Kessler, D.S. and B.G. Cour-Palais. "Collision Frequency of Artificial Satellites: Creation of a Debris Belt." In Space Systems and Their Interactions with Earth's Space Environment, edited by H. B. Garrett and C.P. Pike, AIAA Press, 707-736, 1980.

Chobotov. "Classification of Orbits with Regard to Collision Hazard in Space." J. Spacecraft 20 (5 1983): 484-490.

Johnson, Nicholas L. and Darren S. McKnight. Artificial Space Debris. Malabar, FL: Orbit Book Company, 1987.

Kessler, D. J., R. C. Reynolds, and P. D. Anz-Meador. Orbital Debris Environment for Spacecraft Designed to Operate in Low Earth Orbit. Lyndon B. Johnson Space Center, Houston, Texas, 1989. NASA TM 100 471.

Meteoroids

Cour-Palais, Burton G. Meteroid Environment Model-1969 [Near Earth To Lunar Surface]. NASA, 1969. NASA SP-8013.

Kessler, D.J. Meteoroid environment model-1970 [Interplanetary and Planetary]. NASA, 1970. NASA SP-8038.

Laurance, M.R. and Brownlee. "The Flux of Meteroids and Orbital Space Debris Striking Satellites in Low Earth Orbit." Nature, September 11,1986 1986, 136-138.

Zook, H.A. "The Velocity Distribution and Angular Directionality of Meteoroids That Impact on an Earth-Orbiting Satellite." LPSC XVIII (1987): 1138-1139.

Leinart, C. and E. Grun. "Interplanetary Dust." In Physics of the Inner Heliosphere, eds. R. Schewnn and E. Marsch. 146. Springer, 1988.

Grun, E. and et al. "Interplanetary dust measurements by the Galileo and Ulysses dust detectors during the initial mission phases." In Proceedings, Hypervelocity Impacts in Space, University of Kent, Canterbury, 173-179, 1991.

Divine, N.T. "Five Populations of Interplanetary Meteoroids." J. Geophys. Res. 98 (E9 1993): 17,029-17,048.

Man-Made

Gladstone, S. and P.J. Dolan. The Effects of Nuclear Weapons. Washington, DC: US Dept. of Defense and US Dept. of Energy, 1977.

Interactions

Oxygen Erosion

Leger, L.J. and J.T. Visentine. "A Consideration of Atomic Oxygen Interactions with the Space Station." J. Spacecraft 23 (5, Sept.-Oct. 1986): 505-511.

Glow

Garrett, H.B., A Chutjian, and S Gabriel. "Space Vehicle Glow and its Impact on Spacecraft Systems." J. Spacecraft and Rockets 25 (5 1988): 321-340.

Contamination

Jemiola, J.M. "Spacecraft Contamination: A Review." In Space Systems and their Interactions with Earth's Space Environment, eds. H. B. Garrett and C. P. Pike. 680-706. 71. New York: AIAA Press, 1980.

Bareiss, L.E., R.M. Payton, and H.A Papazian. Shuttle/Spacelab Contamination Environment and Effects Handbook--Second Edition. 2nd Ed. ed., Vol. MCR-85-583. Denver, CO: Martin Marietta Aerospace, 1986.

Hypervelocity Impacts

Cour-Palais, Burton G. "Meteroid Protection By Multiwall Structures". 1969. AIAA Paper No. 69-372.

Cour-Palais, Burton G. "Hypervelocity Impact In Metals, Glass And Composites." Int. J. Impact Engng 5 (1987): 221-237.

Spacecraft Charging

References

Gurevich, A.V., L.P. Pitaevskii, and V.V. Smirnov. "Ionospheric Aerodynamics." Sov. Phys. Usp. (Eng. Trans.) 99(1-2) (1970): 595.

Grard, R.J.L., ed. Photon Particle Interactions with Surfaces in Space. Hingham, MA,: D. Reidel, 1973.

Garrett, H.B. "The Charging of Spacecraft Surfaces." Rev. Geophys. 19 (1981): 577-616.

Whipple, E.C. "Potentials of Surfaces in Space." Rep. Prog. Phys. 44 (1981): 1197-1250.

Hastings, D.E. "A Review of Plasma Interactions with Spacecraft in Low Earth Orbit." J. Geophys. Res. 100 (A8, August 1995): 14,457-14,483.

Conferences

Pike, C.P., and Lovell (editors). Proceedings of the Spacecraft Charging Technology Conference. AFGL-TR-77-0051, 1977.

Stevens, N.J. and C.P. Pike (eidtors). Spacecraft Charging Technology 1980. NASA CP 2182--AFGL-TR-81-0270, 1981.

Olsen, R.C. (editor). Proceedings of the Spacecraft Charging Technology Conference, 1989, Naval Postgraduate School, Monterey, CA, Oct 31-Nov 3, 1989.

Standards and Guidelines

Electromagnetic Compatibility Requirements for Space Systems. United States Air Force, U.S. Government Printing Office, 1987. Military Standard MIL-STD 1541A.

Purvis, C.K., H.B. Garrett, A.C. Whittlesey, and N.J. Stevens. Design Guidelines for Assessing and Controlling Spacecraft Charging Effects. NASA, 1984. NASA Technical Paper 2361.

Whittlesey, A.C. Avoiding Problems Caused by Spacecraft On-Orbit Internal Charging Effects. NASA, 1998. Technical Handbook NASA-HDBK-4002.

General Information

DeForest, S.E. "Spacecraft Charging at Synchronous Orbit." J Geophys. Res. 77 (1972): pp.651-659.

DeForest, S.E. and C.E. McIlwain. "Plasma Clouds in the Magnetosphere." J. Geophys. Res. 76 (1971): 3587.

Balmain, K.G. "Surface Discharge Effects." In Space Systems and Their Interactions with the Earth's Space Environment, eds. H. B. Garrett and C. P. Pike. 276-298. Progress in Astornautics and Aeronautics, 71. NY: AIAA Press, 1980.

Besse, R.L. and A.G. Rubin. A Simple Analysis of Spacecraft Charging Involving Blocked Photoelectron Currents. AFGL, 1980.

Parker, L.W. "Plasmasheath-Photosheath Theory for Large High-Voltage Space Structures." In Space Sys. and Their Interact. with Earth's Space Envir., eds. H.B. Garrett and C.P. Pike. 477-522. 71. AIAA Press, NY, 1980.

Garrett, H.B., D.C. Schwank, P.R. Higbie, and D.N. Baker. "Comparison Between the 30-80 keV Electron Channels on ATS-6 and 1976-059A During Conjunction and Application to Spacecraft Charging Prediction." J. Geophys. Res. 85 (1980): 1155-1162.

Leung, P. "Discharge Characteristics of a Simulated Solar Array." IEEE Trans. Nucl. Sci. NS-30 (1983): 4311.

Gussenhoven, M.S. "Geosynchronous Environment for Severe Spacecraft Charging ." J. Spacecraft and Rockets 20 (1983): 26-34 .

Gussenhoven, M.S. "High Level Spacecraft Charging in the Low Altitude Polar Environment." J. Geophys. Res. 90 (1985): 11,009.

Evans, R., H.B. Garrett, S. Gabriel, and A.C. Whittlesey. "A Preliminary Spacecraft Charging Map for the Near Earth Environment." In Spacecraft Charging Technology Conference in Naval Postgraduate School, edited by R.C. Olsen, 1989.

Plasma Interactions

Bourdeau, R.E. "On the Interaction Between a Spacecraft and an Ionized Medium." Space Sci. Rev. 1 (1963): 719-728.

SPACE ENVIRONMENT REFERENCES (Cont.)

Singer, S.F. editor, Interactions of Space Vehicles with an Ionized Atmosphere. NY: Pergamon, 1965.

Al'pert, J.L., A.V. Gurevich, and L.P. Pitaevskii. Space Physics With Artificial Satellites. NY: Consultants Bureau, 1965.

Fournier, G. "Electric Drag ." Planet. Space Sci. 18 (1970): 1035-1041 .

Al'pert, J.L. "Wave-Like Phenomena in the Near-Earth Plasma and Interactions with Man-made Bodies." In Handbook Physics, Geophysics III (IV), 217-350. 1976.

Radiation Interactions

Books

Janni, J.F. "Proton Range-Energy Tables, 1 keV-10 GeV, Part 1." 150-339. Vol 27. Atomic Data and Nuclear Data Tables: 1982.

Janni, J.F. "Proton Range-Energy Tables, 1 keV-10 GeV, Part 2." 341-529. Vol. 27. Atomic Data and Nuclear Data Tables: 1982.

Messenger, G.C. and M.S. Ash. The Effects of Radiation in Electronic Systems. New York, NY: Van Nostrand Reinhold Co., 1986.

Frederickson, A.R., D.B. Cotts, J.A. Wall, and F.L. Bouquet. Spacecraft Dielectric Material Properties and Spacecraft Charging. Vol. 107. AIAA Progress in Aeronautics and Astronautics, Washington, D.C.: AIAA, 1986.

Jordon, T.M. NOVICE: A Radiation Transport/Shielding Code; Users Guide. Experimental and Mathematical Physics Consultants, 1987. 87.01.02.01.

Radiation Owner's Manual. National Semiconductor Corporation, 1999.

Summaries

Garrett, H.B. "Radiation Environments within Satellites." In IEEE Nuclear and Space Radiation Effects Conference Short Course in Snowbird, UT, edited by A. Johnstone, IEEE, II.1-II.160, 1993.

Dyer, C. Space Radiation Environment Dosimetry. In IEEE Nuclear and Space Radiation Effects Conference Short Course, 1998.

Papers

Adams, J.H., Jr. , R. Silverberg, and C.H. Tsao. Cosmic Ray Effects on Microelectronics, Part I: The Near-Earth Particle Environment. Naval Research Laboratory, Washington D.C., 1981. NRL Memorandum Report 4506.

Adams, J.H., Jr. , J.R. Letaw, and D.F. Smart. Cosmic Ray Effects on Microelectronics, Part II: The Geomagnetic Cutoff Effects. Naval Research Laboratory, Washington D.C., 1983. NRL Memorandum Report 4506.

Tsao, C.H., R. Silberberg, J.H. Adams Jr., and J.R. Letaw. Cosmic Ray Effects on Microelectronics, Part III: Propagation of Cosmic Rays in the Atmosphere. Naval Research Laboratory, Washington D.C., 1984. NRL Memorandum Report 4506.

Adams, J.H., Jr. Cosmic Ray Effects on Microelectronics, Part IV. Naval Research Laboratory, Washington D.C., 1986. NRL Memorandum Report 5901.

Martin, K.E., M.K. Gauthier, J.R. Coss, A.V. Dantas, and Price W.E. Total-Dose Radiation Effects Data for Semiconductor Devices 1985 Supplement. Jet Propulsion Laboraatory, Pasadena, CA, 1986. Volume I, Volume II, Part A, and Volume II, Part B JPL Publication 85-43.

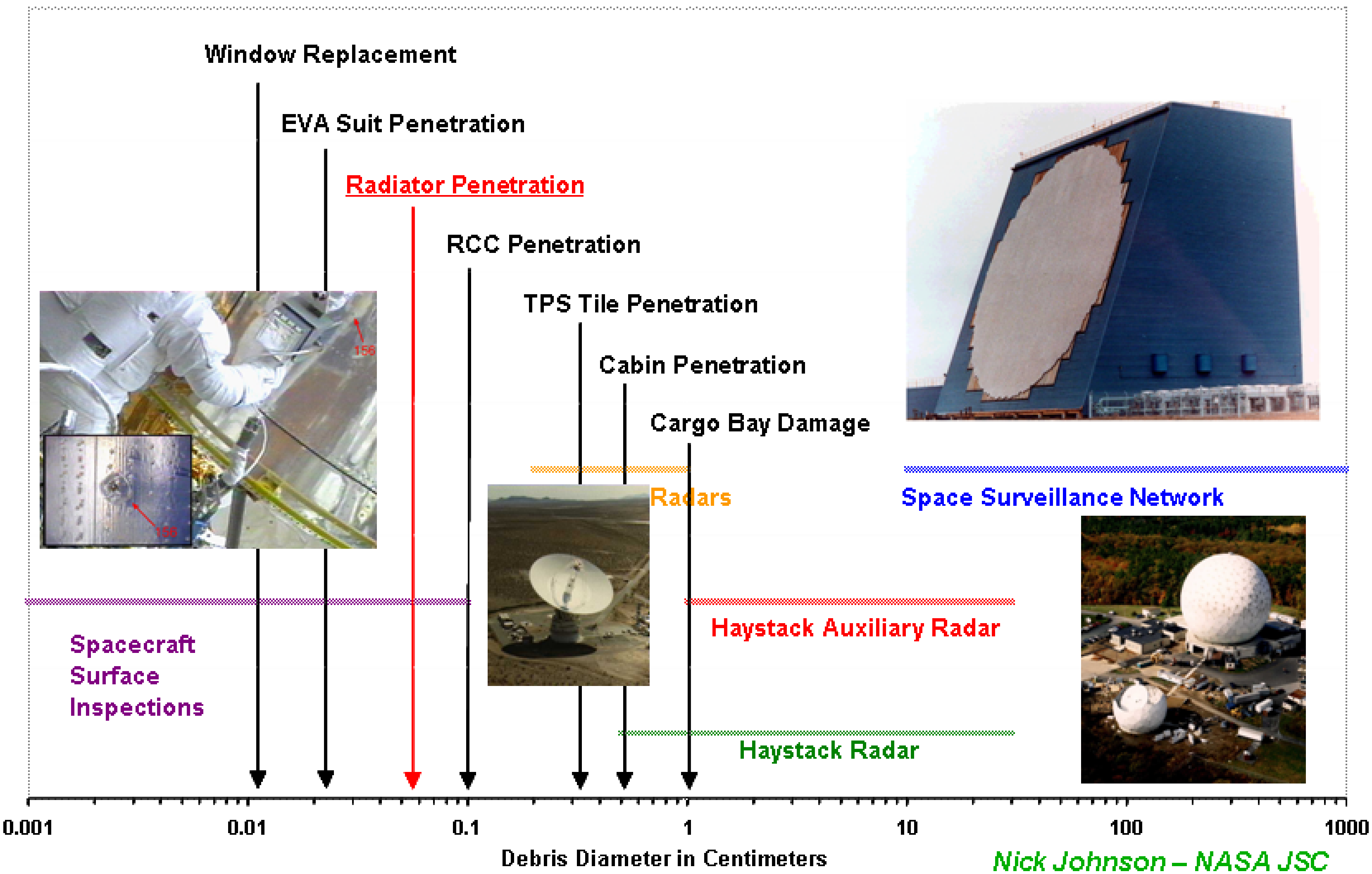
SPACE ENVIRONMENTS AND INTERACTIONS REFERENCES

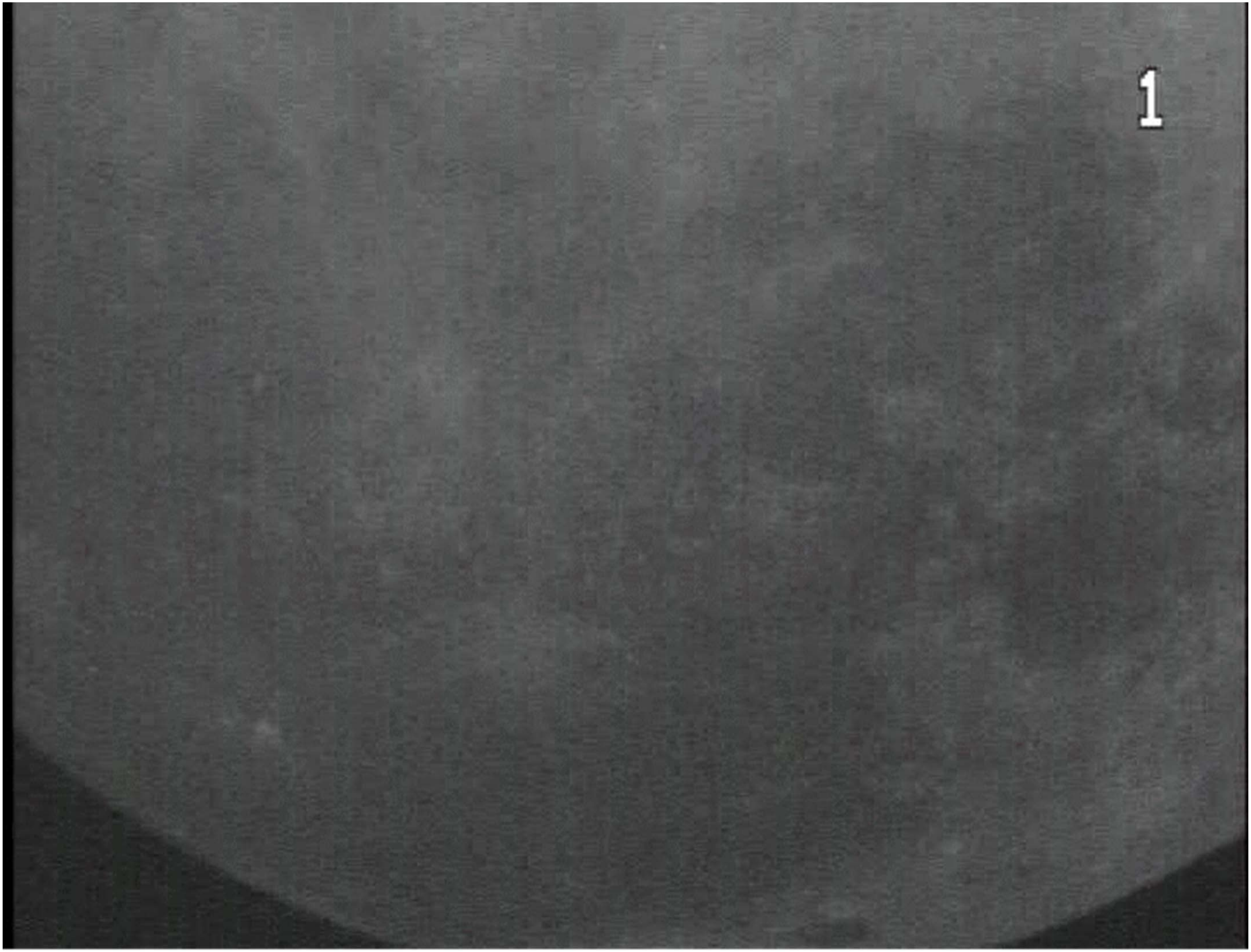
USEFUL INTERNET SITES FOR SPACE ENVIRONMENT EFFECTS

http://envnet.gsfc.nasa.gov/	GSFC (EnviroNET) Homepage
http://see.msfc.nasa.gov/	MSFC SEE Homepage
http://akebono.tksc.nasda.go.jp/	Japanese SEE Homepage
http://crsp3.nrl.navy.mil/creme96/	CREME96 Homepage
http://sat-nd.com/special/index.html	Recent Satellite Outages and Failures
http://nppp.jpl.nasa.gov/	NASA EEE Space Parts Program
http://standards.nasa.gov/	NASA TECHNICAL STANDARDS PROGRAM
http://eis/engstnd/standard/engstnd.htm	Space Engineering Standards (JPL)
http://www.sel.noaa.gov/today.html	Today's Space Weather
http://spaceweather.com/	The NASA Space Weather Bureau
http://www.sec.noaa.gov/	NOAA Space Environment Center
http://www.ngdc.noaa.gov/	National Geophysical Data Center
http://geomag.usgs.gov/	USGS Geomagnetism Program
http://www.ngdc.noaa.gov/seg//potfld/tab1igrf.html#IGRF95	International Geomagnetic Reference Field
http://www.geolab.nrcan.gc.ca/geomag/e_digdat.html	Canadian Digital Magnetometer Data
http://medicine.wustl.edu/~kronkg/leonids.html	Leonid Meteor Shower
http://www.astro.ufl.edu/~oliver/xyz/	METEM Model FTP Site (Prof. John Oliver)
http://www.imo.net/index.html	International Meteor Organization Index
http://www.jpl.nasa.gov/releases/98/glrings.html	Jupiter's rings
http://sn-callisto.jsc.nasa.gov/model/modeling.html	Debris Models
http://www.geo.mtu.edu/weather/aurora/	The Aurora
http://www.pfrr.alaska.edu/~pfrr/AURORA/ACTV.HTM	Alaska Aurora Movies
http://www.ngdc.noaa.gov/dmsp/	DMSP Auroral Photos (Latest Aurora)
http://www.ngdc.noaa.gov/stp/GOES/goes.html	GOES Daily Satellite Data (Geosynchronous)
http://nssdc.gsfc.nasa.gov/cd-rom/cd-rom.html	NSSDC CD Catalog of Space Data
http://www.npi.msu.su/INP/SRD/lop.html	Russian Radiation Models
http://www.ipex.cz/klet/www.html	Astronomical Sites (Asteroid Orbits, etc.)
http://www.stsci.edu/pubinfo/Latest.html	HST Pictures
http://spacelink.msfc.nasa.gov/.index.html	Space Link Educational Data Base/PC Programs
http://www.jpl.nasa.gov/	JPL Homepage
http://www.sni.net/saa/digest.htm	Space Analytics Associates List of Useful URLs
http://www.spacecom.af.mil/usspace/links.htm#wx	US Space Command Space Weather Links
http://www.nrl.navy.mil/clementine/	NRL Clementine Site
http://www-vsbs.plh.af.mil/vsbs-projects.html	AFRL Space Hazards Branch Projects
http://umbra.nascom.nasa.gov/spd/	NASA Space Physics--Mission Descriptions
http://list.cup.cam.ac.uk	My Spacecraft-Environment Interactions Book

Environments

Potential Shuttle Damage




1